THREE-COLOR PRINTING

The first printing is made with yellow ink; the second with red alone; and the fourth with blue only. The third impression is made by combining red and yellow. The finished print is a combination of the three colors. Notice the various colors and shades. See page 326.

# ESSENTIALS OF MODERN PHYSICS

BY

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# PREFACE

WHILE the belief seems to be quite common that the World War revolutionized the sciences of physics and chemistry, it is a fact that the fundamental principles of these sciences were unchanged. It is true, however, that many new applications of well-known principles were developed, and some more or less obscure processes came to be used on a large scale. These interesting applications have been brought to the attention of the general public through the press, as well as through the actual experience of thousands of young men in the army. Thus the interest in both physics and chemistry has developed to a greater extent within the last few years than it did during the preceding quarter of a century.

No subject in the secondary school course of study touches the student's life more closely than elementary physics. No subject is better fitted to develop the reasoning powers, or to cultivate the uncommon faculty known as "common sense." From the time the pupil opens the water faucet in the morning until he snaps off the electric light upon retiring, he is constantly applying or observing some of the principles of physics. These principles may be connected with the automobile, the street car, or motion pictures; or they may have to do with the more prosaic wheelbarrows, buck-saws, or jack-knives.

Although the applications of physics are so common, yet any attempt to present the essentials of the subject to pupils of high school age is certain to meet with many real difficulties. For this reason the author feels that it is important above all else to keep the pupil's point of view ever in mind, that great care must be taken to use very simple

language in explaining the fundamental principles of physics, and that the illustrative material, both in subject matter and through devices used to aid the understanding visually, must be chosen with special reference to its appeal to the young mind.

The method followed in this book uses familiar illustrations to introduce each principle of physics to be studied. The principles are then clearly and concisely stated, and finally clinched by an extended use of practical applications. No attempt has been made to use smaller type to indicate less important topics, since pupils generally assume that matter set in such type is to be omitted. Probably more topics are discussed than the average student can master. The matter to be taught often depends upon local conditions or it may vary with the class itself, hence the choice is left to the discretion of the instructor. In some simple problems, those of the coefficient of linear expansion for example, formulas have been discarded because they look complicated and seem more difficult to the pupil than the problems themselves. An effort is thus made to develop analytical methods of solving problems. The usual formulas are listed in the appendix for the benefit of teachers who prefer to use them.

A discussion of the automobile is taken up in the last chapter of this book. Some new material is added, and attention is then called to a method by which the study of the automobile can be used to review the whole subject of physics. If teachers prefer, this chapter may be used for reference during the study of other topics. Thus the transmission system may be studied in connection with gear wheels in mechanics, the radiation system with heat distribution, the clutch, brakes, and non-skid tires with friction, the carburetor with the gas engine, and non-glare lenses under diffusion of light. Very few important principles of physics are not exemplified in the construction and operation of this compound machine.

# ACKNOWLEDGMENTS

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Naturally the most up-to-date information and the best illustrative material pertaining to many topics in physics are in the hands of the manufacturers. The author has found them very willing to coöperate in educational work. He is especially pleased to acknowledge the courtesy of the following manufacturers who have assisted by furnishing illustrative material: Aermotor Co.; American Telegraph & Telephone Co.; Bausch & Lomb Optical Co.; Cadillac Motor Car Co.; Central Scientific Co.; Chicago Apparatus Co.; Chicago Pneumatic Tool Co.; C. G. Conn, Ltd.;

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# FULL-PAGE ILLUSTRATIONS

ESSENTIALS OF MODERN PHYSICS

# CHAPTER 1

# INTRODUCTORY

**1. Physics — Definition and Scope.** *Physics is often defined as the science which treats of matter and energy.* Such a definition is by no means exclusive; astronomy, chemistry, geology, and some other sciences also deal with matter and energy. The very fact that it is so difficult to give a good definition of physics shows the close relationship between certain sciences. *Physics may also be defined as that branch of science which deals with the physical changes taking place in matter.*

Many questions pertaining to everyday life are constantly arising. Boys are especially interested in machinery; hence the questions, "What is it for?" and "How does it work?" It is of interest to inquire how coal and heat energy are related to the steam-engine, and gasoline to the automobile. "What is color?", "How is electricity produced?", and "What are its effects?" are examples of the questions that we expect physics to answer for us.

Physics also deals with measurement. While quantitative work is usually not so fascinating as the study of causes and effects, yet a few illustrations will suffice to show its importance. A canoe displaces only a few cu. ft. of water, hence it is apt to sink if more than three or four persons enter it; a large steamship displaces thousands of tons of water, and it can carry safely thousands of people. The manufacturer of boats deals with measurements and figures to determine the number of pounds a vessel can carry safely. Meters are used to determine the amount of

water, gas, and electricity a consumer is using. We buy lamps of a certain candle-power, and the man who is buying a car is interested in the number of horse-power it can develop.

In each of the subdivisions of physics, — *mechanics*, *heat*, *sound*, *light*, and *electricity*, — the questions for which we seek an answer are, "What does it do?", "How does it work?", and since it affects our pocket-book or our safety, "How much can it do?", and "At what cost?"

**2. Matter Defined.** Anything that occupies space or takes up room is called *matter*. Wood, iron, air, water, copper, and salt are all examples of matter. Heat, light, and electricity are not matter, since they do not take up room or have weight.

**3. Structure of Matter.** Theoretically a piece of marble may be broken into two pieces, those two into four, and so on to infinity. In reality, matter cannot be subdivided beyond a certain point without losing its identity. The smallest particle into which matter can be subdivided without destroying its *characteristic* properties is called a *molecule*.

No one has ever seen a molecule; these particles are so small that the best microscope fails to reveal them. Suppose a drop of water were magnified until its diameter equals that of the earth; if the molecules at the same time were correspondingly increased, it is estimated they would appear about the size of oranges. By indirect methods it has been learned that one cubic centimeter of air at standard conditions contains $27 \times 10^{18}$ molecules. While the molecules are so very small, yet they are not relatively near neighbors; the space between them is much greater than that occupied by the molecules themselves.

The molecule is made up of *atoms*. In the science of chemistry the unit of matter is the atom. In the laboratory the chemist builds up new molecules from atoms, breaks up the molecules of compounds into their atoms, or arranges the atoms in the molecule.

Until about a score of years ago scientists believed the atom to be the smallest particle of matter, incapable of subdivision. Since the discovery of the X-rays and the isolation of radium, chemists and physicists are quite certain that the atom is not a simple unit, but is really quite complex. Atoms consist of nuclei surrounded by electrically charged particles called *corpuscles* or *electrons*. The electron is about $\frac{1}{1800}$ as heavy as the lightest atom known.

**4. States of Matter.** Every one knows that matter exists in three states: *solids*, *liquids*, and *gases*. Solids have a definite volume and a definite shape; liquids have a definite volume, but they take the shape of the containing vessel; gases have neither a definite shape nor a definite volume. Gases not only take the shape of the containing vessel, but they expand and fill the vessel, no matter what its volume. Water readily changes to ice, a brittle solid, if it is cooled to 32° F.; when the temperature is increased to 212° F., it is converted into steam, which is a gas or vapor. In solids the molecules cling quite firmly together and do not change their relative position readily; hence solids have a definite shape. In liquids the attraction between the molecules is less, and they slide over one another quite readily. For this reason liquids change their shape unless they have lateral support. In gases the molecules move so freely that they tend to separate, hence the indefinite expansion.

Both liquids and gases flow freely; hence both are called *fluids*, from the Latin word *fluere*, which means *to flow*. The division line between solids and liquids is not always a definite one. It is rather difficult to classify a substance like sealing wax, which breaks when struck a sharp blow, but flows under pressure. Sometimes a *viscous* substance, like tar, becomes so stiff in cold weather that it flows with difficulty. Since heat causes the molecules of substances to move more rapidly, an increase in temperature promotes fluidity.

**5. Changes in Matter.** There are many changes taking place in matter. Wood burns; water freezes; salt dissolves in water; milk sours. These are examples of hundreds of changes occurring daily. Changes in matter are of two kinds, *physical* and *chemical.* If the identity of the substance is not destroyed, the change is *physical;* if a new substance with new characteristic properties is formed, the change is *chemical.* The freezing of water and dissolving salt in water are examples of physical changes. The burning of wood and the souring of milk are examples of chemical changes. *Physics* deals with *physical* changes; *chemistry* with *chemical* changes.

**6. Indestructibility of Matter.** We may change the form of matter or change its state, but the amount of matter remains the same. A block of ice weighs the same as the water from which it was formed. The iron in a piece of iron rust has the same weight as the iron from which the rust was formed. While we cannot destroy matter even by means of a chemical change, neither can we create matter. Hence the total quantity of matter in the universe is the same to-day as yesterday. The fact that matter cannot be created or destroyed is often called the *law of the conservation of matter.*

**7. Properties of Matter.** Different substances have different properties. Steel is hard, hence it makes good cutting tools. Since heat passes through aluminum readily, this metal is used for cooking utensils. Since the behavior of a substance under given conditions depends upon its properties, it is quite important for the student of physics to know something concerning the properties of matter. Certain *general* properties are common to all matter. There are also many *special* properties which are common to certain substances only. The use to which a substance is put depends upon its *special* properties. Steel is used extensively, because it is hard and tough.

## A. GENERAL PROPERTIES.

**8. Extension.** If matter occupies space, it must have length, breadth, and thickness. In other words, all matter has *volume*. When we studied arithmetic, we learned how to find the volume of rectangular solids *directly* by obtaining the product of their length, breadth, and thickness. By using an *indirect* method in physics we shall learn how to find the volume of any solid, no matter how irregular it may be. That gases occupy space or have the property of *extension* is evident from the increase in the size of pneumatic tires when inflated.

**9. Mass and Weight.** *The mass of a body is the measure of the quantity of matter it contains.* The mass of a body does not vary.

*Weight is the measure of the earth's attraction for a body.* The weight of a body may vary, since it depends upon two factors: (*a*) the mass or quantity of matter it contains; and (*b*) its location on the earth's surface or its distance from the center of the earth. An iron rod contains the same quantity of matter *any* place on the earth or 1000 miles above the earth; its *mass* is constant. As its distance from the center of the earth varies, however, the attraction of the earth for it will also vary, thus causing its *weight* to change.

**10. Impenetrability.** When we pour water into a bottle, the *air* bubbles out with a gurgling sound as the *water* enters. When a nail is driven into a board, it does not penetrate the wood, but it pushes the fibers aside. The same is true in sewing; the needle pushes the fibers of the cloth aside. From these and other examples, we are led to conclude that *no two objects can occupy the same place at the same time.*

This general property of *impenetrability* makes it possible to find the volume of irregular solids indirectly. Suppose we

put a little water in a graduated cylinder as in Fig. 1, and note the mark to which the water rises. If we then add the solid, the water will rise, since both cannot occupy the same space at the same time. The difference between the two graduation marks equals the volume of liquid displaced. The volume of the liquid displaced is just equal to the volume of the solid. Any non-porous, insoluble solid displaces its own volume of water when submerged.

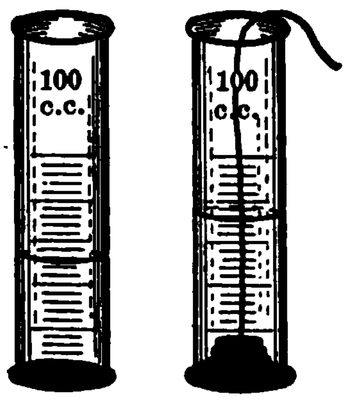


FIG. 1.— Matter is impenetrable.

**11. Porosity.** All matter is more or less porous. The large pores of the sponge cannot escape detection. The pores of an unglazed brick are not so obvious, but water readily finds its way through the brick. Cistern water is often filtered through brick. Iron and silver have still smaller pores, but water under enormous pressure can be forced through them. When a given quantity of alcohol and water are shaken together the volume decreases slightly, due to the porous nature of these liquids.

**12. Inertia.** A street-car cannot stop without the application of some force; neither can it begin to move unless some force is applied to start it. We are all too familiar with the sudden lurch with which we are thrown forward when a car stops suddenly or are jerked backward when the car starts quickly. Matter has no ability in itself to move or to stop moving. Matter is *inert,* which means it is lazy or inactive. On account of the general property of inertia, *bodies in motion tend to remain in motion; bodies at rest tend to remain at rest.* If one leaps from a rapidly moving car, he is likely to fall in the direction the car is going, since his feet are stopped by the friction of the pavement, while inertia impels his body forward. If a car moving at high speed suddenly strikes a tree, the driver is apt to be thrown through the wind-shield.

### *B.* SPECIAL PROPERTIES

**13. Tenacity.** A body that is not easily pulled apart is said to be *tenacious*. The tenacity of any given material, or its tensile strength, is measured by the force needed to break unit cross-sectional area. The length of a wire does not affect its tenacity. If a load is held for a considerable

FIG. 2. — The Brooklyn Bridge, which is over 1 mile long and 85 ft. wide, is supported by four cables. Each cable is made up of 6300 steel wires, No. 7 gauge. These wires are wrapped in a solid cylinder over 15 in. in diameter. Each cable has a tensile strength of 12,000 tons.

time, the tenacity of the wire is somewhat diminished; hence a wire may be broken eventually by a load which it held safely at first. Engineers call this the *fatigue* of metals. Of the metals steel has the greatest tensile strength; a block of high-grade steel one square inch in cross-sectional area can sustain a load of 200,000 lb. The cables of the Brooklyn Bridge are over one foot in diameter. These cables sustain the weight of the bridge and its load. See Fig. 2. The Hell

Gate Bridge over the East River also serves to illustrate the strength of steel. (Fig. 3.)

**14. Ductility.** Gold, silver, platinum, copper, and iron may be drawn into wire; they are said to be *ductile.* Very fine wires are often drawn through a diamond die. A small hole is first drilled in the diamond; one end of the wire is pointed enough so it will pass through the opening; as the remainder of the wire is pulled through the die, it is reduced in diameter. For use in the filaments of certain electric

FIG. 3. — Hell Gate Arch Bridge is the longest arch in the world. The span between the towers is 1016 ft. and 10 in. The bridge, which is 95 ft. wide, carries four railroad tracks.

lamps tungsten wire is sometimes drawn out until its diameter is only one sixth that of an average hair. Platinum is the most ductile of metals; it has been drawn into wires only 0.00003 inch in diameter. Glass is very ductile at a high temperature. Quartz is spun so fine that it is impossible to see the threads with the naked eye.

**15. Malleability.** Iron, copper, lead, aluminum, platinum, and gold may be hammered or rolled into sheets; they are said to be *malleable.* Gold is so malleable that it has been beaten into sheets so thin that it requires 250,000 to make a pile one inch high. It would require about 1000 such sheets to equal in thickness a single leaf of this book. Such thin sheets of a metal which is generally considered

opaque are quite translucent. Fig. 4 shows a press used for making steel plates. Some large presses exert a force of 14,000 T.

**16. Hardness.** We call a substance hard if it cannot be easily scratched or abraded. The term *hard* is only a relative one. For example, glass is harder than wood, but it is easily scratched by the diamond. Soapstone, or steatite,

FIG. 4. — 1000-ton flanging press. Hydraulic presses exert a force of a few tons; or in the case of the very large ones, the force exerted is from 12,000 to 14,000 tons.

is so soft it may be easily scratched with the thumb-nail; it is often pulverized for use in talcum powder. When two substances of unequal hardness are rubbed together, the harder always wears away the softer the more rapidly, unless the soft substance is driven at a high velocity. Hard substances, like sand, emery, carborundum, and diamond dust are used extensively for cutting, grinding, and polishing.

**17. Brittleness.** A substance that is easily broken is said to be *brittle.* Students sometimes confuse hardness and brittleness. Glass is hard and brittle, but steel and some other substances may be hard and tough. Steel is *tempered* to give it the proper degree of hardness; its toughness is increased by heating it and then cooling it slowly. Glassware is cooled slowly to make it less brittle. The process is called *annealing.*

## C. MEASUREMENT

**18. Two Systems of Measurement.** Unfortunately we have two systems of measurement in use in the United States. The student is more or less familiar with the *English System,* but since the tables are easily forgotten, the more important values are given in the appendix for reference.

Practically all civilized countries except Great Britain and the United States use the *Metric System* exclusively. This system originated in France at the time of the French Revolution. It is a decimal system very similar to the table for United States money.

If the Metric System were the only one in use, the whole system of weights and measures could be taught in a few minutes, since there are only three words and a half dozen prefixes to be learned. The *meter* is the unit of length; the *liter* is the unit of capacity; and the *gram* is the unit of weight. The prefixes used for the subdivisions of these units are derived from the Latin: *milli,* $\frac{1}{1000}$; *centi,* $\frac{1}{100}$; *deci,* $\frac{1}{10}$. The prefixes used for the multiples of these units are of Greek derivation: *deca,* 10; *hecto,* 100; and *kilo,* 1000. The only difficult thing about the Metric System arises from the fact that it must sometimes be compared with the more complicated English System.

**19. Metric Tables.** In the Metric System the units are based upon natural standards. The *meter* is approximately equal to $\frac{1}{10,000,000}$ the distance from the Equator to the Pole.

The *standard* meter equals the distance, measured at 0° C., between two lines scratched on a platinum-iridium bar kept at the archives in Paris. From this original standard thousands of copies have been made and distributed. The table of length in the Metric System is as follows:

| | | | |
|---|---|---|---|
| 10 millimeters | (mm.) | make | 1 centimeter |
| 10 centimeters | (cm.) | make | 1 decimeter |
| 10 decimeters | (dm.) | make | 1 meter |
| 10 meters | (m.) | make | 1 decameter |
| 10 decameters | (Dm.) | make | 1 hectometer |
| 10 hectometers | (Hm.) | make | 1 kilometer (Km.) |

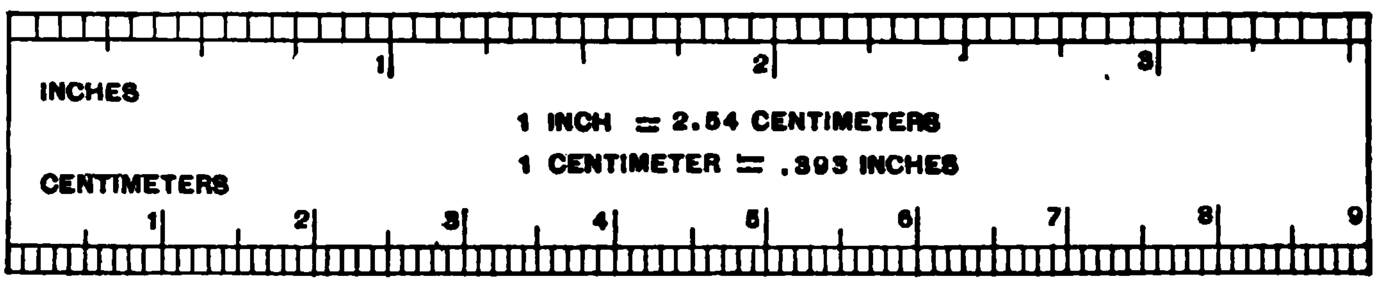


FIG. 5. — Comparison of Metric and English units of length.

Fig. 5 shows the relation between the English and the Metric units of length. *One inch equals 2.54 cm.* The *meter equals 39.37 inches;* the yard equals $\frac{3600}{3937}$ of a meter.

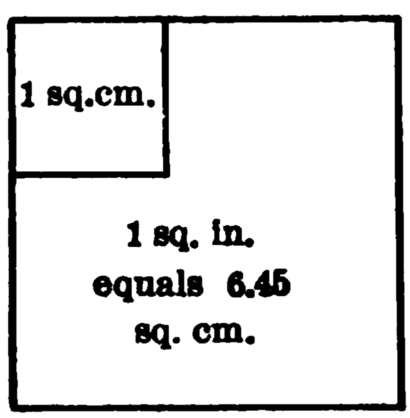


FIG. 6. — Comparison of the Metric and English units of area.

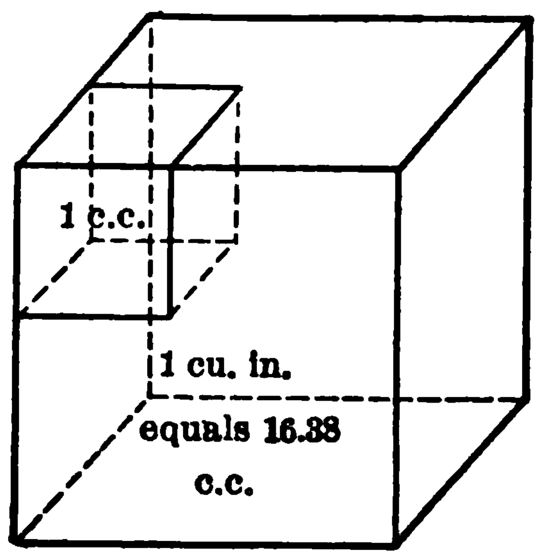


FIG. 7. — Comparison of the Metric and English units of volume.

For measuring surfaces or areas the square meter is used, Fig. 6. The cubic meter is sometimes used for measuring

volumes. Vessels used for measuring liquids are often graduated in cubic centimeters (c.c.). The abbreviation cm.$^3$ is often used instead of c.c. Fig. 7 shows the relative sizes of one c.c. and one cu. in.

Given a metric ruler, one can easily construct a *liter* measure, since a cubical box 10 cm. on a side holds exactly 1 liter. The liter is equivalent to 1000 c.c., or to 1 cu. dm. The liter is used as the unit of capacity for both dry and liquid measure. It is slightly smaller than our dry quart and a little larger than the liquid quart. The table for capacity differs from the metric table of length only in the substitution of the word "liter" for "meter." Fig. 8 shows the relative sizes of the *dry quart*, the *liter*, and the *liquid quart*.

FIG. 8.— Comparison of Metric and English units of capacity.

The *gram* is the unit of weight in the Metric System, but it is so small that the *kilogram* is more often used. The kilogram equals 2.2046 lb. A new 5-cent piece weighs almost exactly 5 grams. A liter vessel (1000 c.c.) holds just 1 kilogram of water at a temperature of 4° C. Therefore *one cubic centimeter of water weighs one gram.* Sometimes the metric ton (M.T.) is used; it equals 1000 kilograms. Fig. 9 shows the comparative size of a pound weight and a kilogram weight.

FIG. 9. — Comparison of Metric and English units of weight.

**20. Time.** The second is the unit of time in both systems. The Metric System is often known as the *centimeter-gram-second* (C.G.S.) system. The English System is known as the *foot-pound-second* (F.P.S.) system.

**21. Density.** *The density of a substance is its weight per unit volume.* In the Metric System density is usually expressed in gm. per c.c.; in the English System it is expressed in lb. per cu. ft. If we wish to find the density of a given substance, we must first weigh it carefully; next its volume must be found either by direct measurement or by the indirect method described in § 10. Then, *weight divided by volume equals density.* Suppose a block of wood which is 10 cm. long, 6 cm. wide, and 4 cm. thick weighs 180 gm. Its volume is 240 c.c. (10 cm. × 6 cm. × 4 cm.). The weight of 1 c.c. equals $\frac{180 \text{ gm.}}{240}$, or 0.75 gm. Therefore the density of the block is 0.75 gm. per c.c. In *the Metric System water has a density of 1 gm. per c.c.*

In the English System the unit of volume used for density determinations is the cu. ft. *One cu. ft. of water weighs 62.4 lb.* Expressed algebraically, $D = \frac{W}{V}$, or $DV = W$. For use in solving problems, a table showing the density of a few common substances is given in the appendix.

## SUMMARY

Physics is a science which treats of matter and energy. It deals with physical changes in matter.

Matter is made up of very small particles called molecules. The molecule, which is the unit in physical changes, is made up of atoms. The atoms in turn contain still smaller particles called electrons. The molecules of matter are always in motion. An increase in temperature accelerates molecular motion.

Matter exists in three states: solids, liquids, and gases. Solids have a definite volume and a definite shape; liquids have a definite

volume, but they take the shape of their container; gases have neither a definite volume nor a definite shape.

Certain properties, such as inertia, impenetrability, extension, weight, and indestructibility are common to all matter. Such special properties as ductility, malleability, tenacity, hardness, and brittleness are peculiar to certain substances.

The student should memorize the following Metric-English equivalents: 1 m. equals 39.37 in.; 1 in. equals 2.54 cm.; 1 kgm. equals 2.2 lb. Other equivalents are given in the appendix.

The density of a substance is the weight of unit volume of that substance. The student should remember that 1 c.c. of water weighs 1 gm.; also that 1 cu. ft. of water weighs 62.4 lb.

## QUESTIONS AND PROBLEMS

1. Name five physical changes and five chemical changes.

2. Could you find the volume of a lump of sugar by using the indirect method described in § 10? Explain.

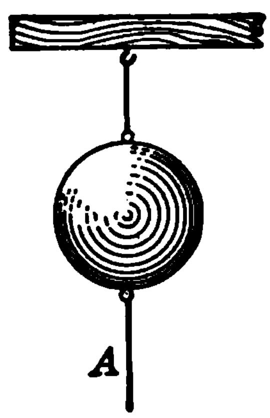


FIG. 10. — A ball has inertia.

3. Show how the property of inertia is exhibited in shoveling coal into a furnace.

4. Account for the jarring of the water-pipes when the water is turned off suddenly.

5. In Fig. 10 the segment of string supporting the ball is from the same piece as the one attached below. If one pulls at $A$ with a quick jerk, the string will break below the weight; if a steady pull is applied, it will break above the weight. Explain.

6. How is the principle of inertia utilized in beating a rug or carpet?

7. Why does a heavy fly-wheel cause machinery to run steadily?

8. Why should one face forward when alighting from a car?

9. Which is longer and how much, 880 yd. or 800 m.?

10. How many pounds are there in 42.8 kgm.?

11. Find your weight in kgm.; your height in meters.

12. A train runs 60 mi. per hr. Find its speed in ft. per sec.; in km. per hr.; in m. per sec.

13. Find the value of 1 foot in cm.; of 1 ounce in gm.

**14.** A substance has a density of 7.8 gm. per c.c. Find the weight of a cubical block of this substance 3 dm. on a side.

**15.** A manufacturer wishes to make a 500-gram brass weight. How many c.c. of brass are needed? See density table in Appendix.

**16.** A box is 2.5 ft. long, 2 ft. wide, and 2 ft. deep. How many pounds of water can the box hold?

**17.** Find the weight of a block of gold 6 in. long, 4 in. wide, and 2 in. thick. Compare with the weight of an ordinary brick.

**18.** Compare the weight of 1 lb. of gold with 1 lb. of feathers. How much heavier is an oz. of gold than an oz. of feathers?

**19.** How many quarts would a grocer get from a bushel of berries if he measured them with a liquid quart measure?

**20.** Explain why shaking or jarring a tree will bring down apples, nuts, etc.

*Suggested Topics.* History of the Metric System and Its Advantages.

## CHAPTER 2

# MECHANICS OF LIQUIDS

### *A.* LIQUID PRESSURE

**22. Liquids Exert Pressure.** If we push a piece of cork or a block of wood under water, it will rise to the surface again as soon as it is released. The water exerts an upward pressure on the block. Force is required to hold a block of wood or a piece of cork under water. *We may define force as a push or pull;* it is usually measured in grams or pounds. Force applied to *unit area* is known as *pressure.* It is the upward pressure which water exerts that causes boats to float. Liquids likewise exert an upward thrust upon bodies that are dense enough to sink, thus causing such bodies to lose part of their weight when submerged.

**23. Liquid Pressure Is Proportional to the Depth.** Just as a brick lying on a table presses upon the table, so water or any other liquid poured into a vessel exerts force or pressure upon the bottom and sides of the vessel. Such force is due to the weight of the liquid. When several bricks are piled upon one another the downward pressure is increased. Likewise every layer of liquid sustains the weight of the layer directly above it, hence the *pressure of a liquid must increase in direct proportion to the depth.* If the unit area pressed upon is 1 sq. cm., as in Fig. 11, then water 1 cm. deep exerts a pressure of 1 gm., which is the weight of 1 c.c. of water; the pressure at a depth of 2 cm. equals 2 gm.; for each cm. increase in depth the increase in pressure

FIG. 11. — Liquid pressure increases with the depth.

is one gm. If the unit area is one sq. ft., water one foot deep exerts a pressure of 62.4 lb. On each sq. in. the pressure is 0.433 lb. for each foot in depth.

**24. Liquid Pressure Is Independent of Direction.** A pile of bricks resting on a table exerts pressure in a *downward* direction only; but the molecules of a liquid move over one another so freely that a liquid takes the shape of its container; therefore we may expect liquids to press outward in a *sidewise* direction. Our study of floating objects convinces us that liquids push upward as well as downward. If we pour mercury into the three tubes shown in Fig. 12 until it stands at the same height in each, and then lower them all into water so that the open ends are at the same depth, the pressure of the water will cause the mercury to rise in the long arm of each tube. At $A$ the water presses *downward;* at $B$ the pressure is *upward;* while at $C$ a *sidewise* pressure is exerted. The mercury stands at the same level in the long arm of each tube. As measured by the mercury columns the pressures are all equal. This is one way of showing that *liquid pressure is independent of direction.*

FIG. 12. — Liquid pressure is equal in all directions.

Since liquid pressure is independent of direction, *it is also independent of the shape of the container.*

**25. Liquid Pressure Is Proportional to Density.** Since a dense liquid like mercury has a greater weight per unit volume than water, it should produce a greater pressure. Experiment shows that *the pressure exerted by a liquid is directly proportional to its density.* The density of mercury is 13.6 gm. per c.c.; hence mercury 10 cm. deep exerts a pressure of 136 gm., just 13.6 times as much as the pressure of that depth of water. Put in the form of an equation,

$$\textit{pressure} = \textit{depth} \times \textit{density}.$$

**26. Direct and Inverse Proportion.** The terms *direct proportion* and *inverse proportion* are used so frequently in stating facts and laws in physics that it may be of value to inquire their meaning. *Two quantities are directly proportional to each other when an increase in one produces a corresponding increase in the other. Two quantities are inversely proportional to each other when an increase in one produces a corresponding decrease in the other.*

In § 23 we learned that liquid pressures are *directly* proportional to the depth. We may plot a graph to show direct proportion, using data obtained by experiment.

Depth of 1 cm., pressure equals 1 gm.
Depth of 3 cm., pressure equals 3 gm.
Depth of 5 cm., pressure equals 5 gm.
Depth of 9 cm., pressure equals 9 gm.
Depth of 12 cm., pressure equals 12 gm.

Suppose we let $O$ represent the origin of the graph, Fig. 13, and measure off on the line $XX'$ distances equivalent to the various pressures. For convenience let us use one small space to represent one gram. Next let us measure off on the line $YY'$ distances *equivalent* to the depth in cm., using one small space to represent 1 cm. Point $A$ represents a pressure of 1 gm. at a depth of 1 cm.; point $B$ represents a pressure of 3 gm. at a depth of 3 cm. In a similar manner we locate the points $C$, $D$, and $E$, and draw a line from the origin of the curve through all these points. This line, $OS$, is a curve of *direct proportion.*

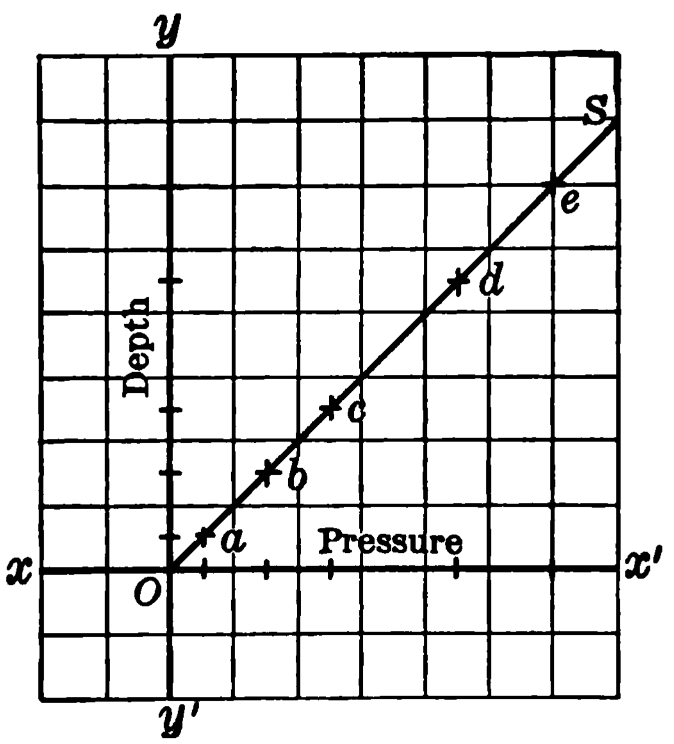



FIG. 13. — Direct proportion curve.

**27. Total Force on the Bottom of a Vessel.** We have learned that the pressure of a liquid, on the bottom of a vessel for example, equals the depth times the density. Since pressure is the force acting on *unit area*, to find the *total force* acting on the bottom of a vessel we merely multiply the area by the pressure. Stated algebraically,

$$\text{total force} = \text{area} \times \text{depth} \times \text{density}.$$

PROBLEM. A box 20 cm. long, 15 cm. wide, and 12 cm. deep is full of water. Find the total force on the bottom of the box.

*Solution.* The area pressed upon is 20 cm.×15 cm., or 300 sq. cm.; the depth of the water is 12 cm., and its density is 1 gm. per c.c.

$$\text{total force} = \text{area} \times \text{depth} \times \text{density}.$$
$$\text{total force} = 300 \times 12 \times 1 \text{ gm., a total of } 3600 \text{ gm.}$$

Had the dimensions in the preceding problem been given in feet, the total force would equal 300×12×62.4 lb., a total of 224,640 lb.

**28. Total Force on the Side of a Vessel.** Very often an engineer wishes to know the total force on the side of a dam. We know that for the area we must always use the *area of the surface pressed upon.* Since pressure is independent of direction, the only question that arises is what depth to use.

Suppose we wish to find the total force on one side of the box whose dimensions were given in § 27. The area of one side is equal to the length times the depth, or 20 cm.×12 cm.; in this case it is 240 sq. cm. The depth at the water surface is 0; at the bottom it is 12 cm. The *average* depth of the surface pressed upon is $\frac{0+12}{2}$, or 6 cm. Thus the total force on one side equals 240×6×1 gm.; the product is 1440 gm.

*In any case total force equals the area of the surface pressed upon times the average depth times the density.*

**29. Applications.** (*a*) *Water seeks its level.* Water stands at the same level in communicating vessels, whatever their shape or relative area. The water in the spout of a tea-kettle stands at the same level as the water in the kettle. The water gauge on a steam boiler is another example. See Fig. 14. The water supply for some cities is drawn from a reservoir higher than any part of the city itself. Since water seeks its level, it readily rises through the waterpipes in the houses to the taps or faucets. If, however, part of a building happens to be higher than the reservoir, the floors above the reservoir will be without water unless a pumping station is installed. Many cities are forced to install such stations, since their water supply is lower than the high buildings. Fig. 15 is a diagrammatic sketch which shows how water may be supplied to cities.

Fig. 14 — Water gauge.

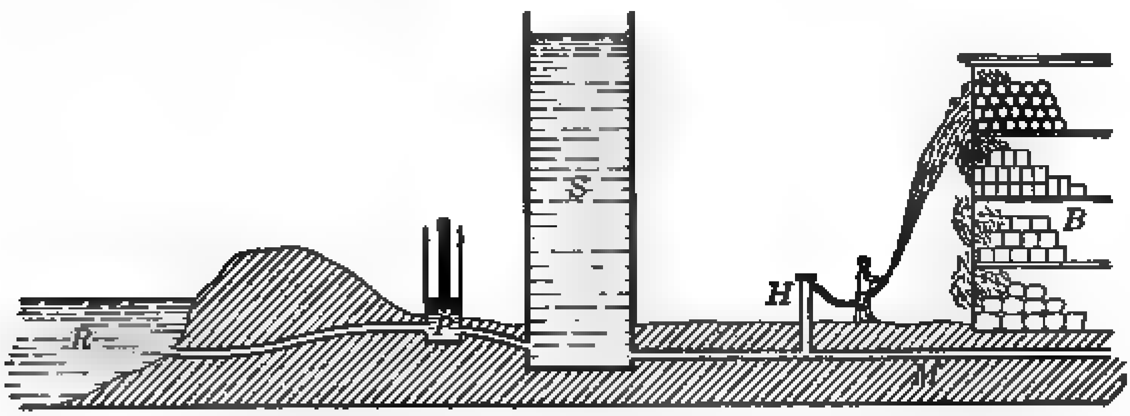



Fig. 15. — City water supply. *R*, reservoir; *P*, pumping station; *S*, stand-pipe; *H*, hydrant; *M*, water main; *B*, building.

The pumping station at *P* pumps the water from the reservoir *R* to the stand-pipe *S*, which is higher than any building in the city. The upper floors of tall sky-scrapers are supplied by independent pumping systems.

The *artesian well* is merely an illustration of the fact that water seeks its level. In Fig. 16, *G* is a layer of water-

saturated gravel between two strata of impervious rock. When a hole is drilled through the upper stratum, the pressure of the water at $A$ and $B$ forces the water out, thus causing a flowing well at $W$.

(*b*) *Pressure on submerged bodies.* We have already learned that the pressure on an area of one sq. ft. submerged to a depth of one foot is 62.4 lb. Since the pressure increases with the depth, it is easy to see that the pressure soon becomes enormous as a body is lowered into water.

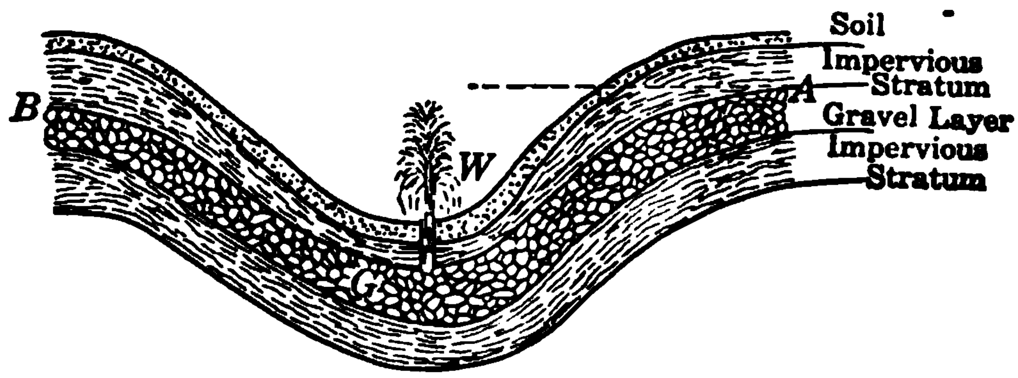



FIG. 16. — Artesian well.

Divers cannot descend in safety to a very great depth, although cases are on record of deep-sea diving to a depth of over 300 ft.

The hull of a vessel must be strong enough to resist the pressure of the water in which it is submerged. This problem becomes a difficult one in constructing submarines.

(*c*) *Total force as related to construction work.* Before building cisterns, tanks, stand-pipes, dams, and canal-locks, the engineer must compute the pressure or the total force to which these structures will be subjected. The amount of material used in constructing dams for storage reservoirs is enormous. Fig. 17 gives an idea of the enormous strength that canal-locks must have, to withstand the total force of the water when the gates are closed.

**30. Measurement of Water Pressure.** Water pressure may be measured by the use of a bent tube partially filled with mercury. When the tube shown in Fig. 18 is attached to a faucet and the water turned on, its pressure is counter-

Fig. 17. — The Panama Canal locks are 900 ft. long, 95 ft. wide, and the water has a minimum depth of 41 ft. Enough concrete was used in the construction of each lock to make a pile as big as the Great Pyramids. The steel gates are 7 ft. thick, 65 ft. long, and from 47 to 82 ft. high; their weight is from 300 to 600 tons.

balanced by the mercury column *ab*. If the tube has a cross-sectional area of one square inch, the weight of the mercury column in pounds equals the water pressure in pounds per square inch. Such a pressure gauge is called an *open mercury manometer*. A *closed manometer* is sometimes used. More often liquid pressure is measured by a

spring gauge, which is calibrated to read directly in pounds per square inch. See Fig. 19. The expression "head of water" or "water head" is in common use among engineers.


FIG. 18. — Open manometer.

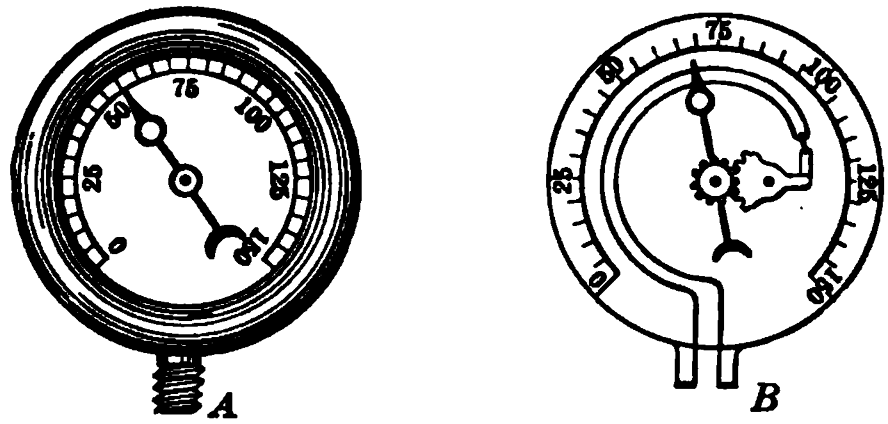



FIG. 19. — Bourdon pressure gauge.

If the difference of levels in communicating pipes is 144 ft., the "water head" is said to be 144 ft. Such a "water head" produces a pressure of 62.4 lb. per sq. in.

### *B.* PRESSURE APPLIED TO LIQUIDS

**31. External Pressure Applied to Confined Liquids.** Suppose we fill the bottle shown in Fig. 20 with water. For convenience let us use a bottle having a neck one square inch in cross-sectional area. As the stopper is shoved into the bottle, pressure is exerted upon the confined liquid. A solid is rigid and transmits pressure only in the direction in which the force acts; but fluids move freely and thus transmit pressure *in every direction.* If we use 10 lb. of force in pushing the stopper into the bottle, we not only produce a pressure of 10 lb. on the surface of the liquid, but this pressure is transmitted *undiminished* so that it acts upon every unit area of the walls and bottom of the bottle.

FIG. 20. — Pascal's bottle.

**32. Pascal's Law.** After carrying out a series of experiments, Blaise Pascal found that one man pushing against

a small piston which fits the opening in a closed vessel filled with water can equal the force of a hundred men who push against a piston of 100 times the area. See Fig. 21. He stated the results of his experiment in the following law: *Pressure applied to any part of an inclosed fluid is transmitted so as to act with undiminished force in any direction. This pressure acts with equal force upon equal areas and at right angles to them.* Pascal's law applies to liquids and gases.

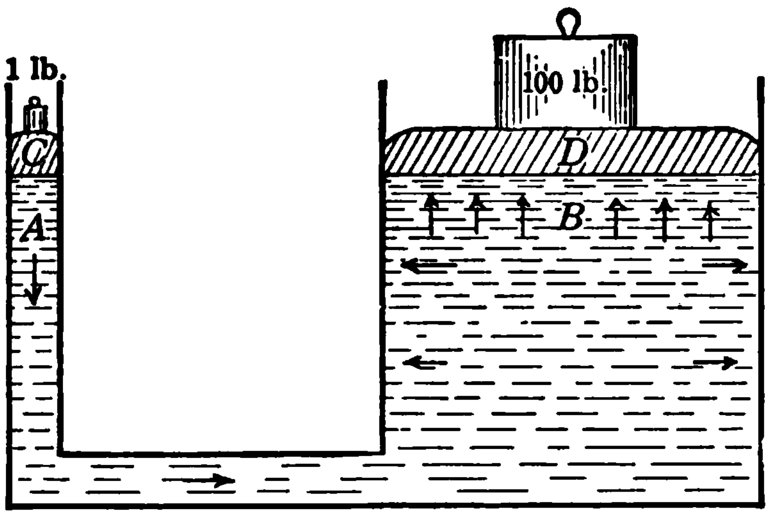



FIG. 21. — Pressure is transmitted equally in all directions.

**33. Transmission of Liquid Pressure Used to Multiply Force.** From Pascal's law, we are led to the following conclusion: If $A$ of Fig. 21 has an area of 1 sq. in. and $B$ an area of 100 sq. in., a weight of 1 lb. lying on the piston $C$ will just balance a weight of 100 lb. on the piston $D$. A force *slightly* in excess of 1 lb. acting downward on the small piston will lift the weight of 100 lb. upon the large piston. From these observations, it is easy to see how it is possible to construct a mechanical device for multiplying force.

The student, however, must never forget one very important fact. In the multiplication of force by any mechanical device, the distance and speed are correspondingly diminished. In other words, *what is gained in force is lost in distance and speed.* Suppose we force the piston $C$ down 10 in.; just 10 cu. in. of water will be forced from $A$ into $B$. The piston $D$ will be lifted only $\frac{10}{100}$, or $\frac{1}{10}$, of an inch. In the time required for $C$ to move 10 in., $D$ moves only $\frac{1}{10}$ of an inch, or $\frac{1}{100}$ as far as $C$. In all mechanical devices, *the product of the acting force times the distance through*

*which it moves equals the product of the resisting force times the distance through which it moves.* Applied to the above case, 1 lb. moving 10 in. is equivalent to 100 lb. moving $\frac{1}{10}$ inch.

**34. The Hydraulic Press.** The commercial hydraulic press differs little from the device illustrated in Fig. 22. A lever is attached to the small piston. As this piston is forced down by means of the lever, oil or water is pumped into the vessel *B*, where it exerts an upward force on the large piston *P*.

FIG. 22. — Diagram of hydraulic press.

The mechanical advantage of a machine equals $\frac{\text{resistance}}{\text{effort}}$;

$$\text{it also equals } \frac{\text{distance effort moves}}{\text{distance resistance moves}}.$$

If we neglect the effect of the lever, the *mechanical advantage* of such a press equals $\frac{A}{a}$, in which $A$ is the area of the large piston, and $a$ the area of the small piston. If the diameters of the pistons are given, mechanical advantage $= \frac{D^2}{d^2}$.

The hydraulic press is used for baling cotton, paper, etc., squeezing the juice from apples and other fruits, expressing oil from seeds, punching holes in steel plates, embossing metals, and lifting enormous weights.

**35. The Hydraulic Elevator.** Fig. 23 shows a simple form of hydraulic elevator, which is an application of Pascal's law. Water from the city mains, or from a reservoir, enters a cylindrical pit through the valve *V*. In this pit it exerts an upward pressure on the piston *P*, which is a shaft whose

length equals the height of the building. Upon the top of this shaft is the elevator cage; both the shaft and cage $C$ are partly counterpoised by the weight $W$. When a cord is pulled, the valve $V$ forms connection with the outlet pipe, and water flows from the pit, thus causing the elevator to descend. The mechanical advantage of the elevator equals

$$\frac{(\text{Diameter of piston})^2}{(\text{Diameter of pipe})^2}.$$

## QUESTIONS AND PROBLEMS

(See density table in Appendix.)

Fig. 23 — Hydraulic elevator.

1. Find the pressure in pounds per sq. in. to which a diver is subjected if he descends to a depth of 200 ft. in sea water, its density being 64 lb. per cu. ft.

2. What force is required to hold a board tightly against a hole 6 ft. long by 4 ft. wide in the side of a ship if the average depth is 20 ft.?

3. What are the advantages of the hydraulic elevator? What are its disadvantages?

4. Find the pressure in grams exerted by a column of mercury 76 cm. high. How high a column of water is needed to produce the same pressure?

5. The surface of the water in a stand-pipe is 200 ft. above the level of a faucet. What pressure is exerted at the faucet?

6. The breast of a dam is 20 ft. long; its vertical height is 30 ft. Find the total force exerted against the dam when the water stands level with the top.

7. The diameters of the pistons of a press are 1 in. and 8 in. respectively. What force must be applied to the small piston to lift a locomotive weighing 96 tons?

**8.** Why is the base of a dam made thicker than the top?

**9.** Water is supplied to a hydraulic elevator at a pressure of 80 lb. per sq. in. If the piston has a diameter of 10 in., what load can it lift?

**10.** A tank is 10 ft. square and 10 ft. deep. Find the total force on the bottom of the tank when it is filled with water. Find the total force on the sides.

**11.** A tank 10 ft. deep is 10 ft. in diameter. If it is full of water, find the total force on the bottom and on the sides.

**12.** What is the pressure in lb. per sq. in. when the "water head" is 500 feet?

## *C.* ARCHIMEDES' PRINCIPLE

**36. Buoyancy of Liquids.** We have already observed that water exerts an upward pressure, or buoyant force, upon objects immersed in it. If the buoyant force of the water is greater than the weight of the object, such an object will float. See Fig. 24. Objects that are denser than water,

FIG. 24. — The Naval hydroplane NC-4 was the first to cross the Atlantic Ocean. Her wing spread is 126 ft., and her extreme length 70 ft. The NC-4 was driven by four 400 H. P. Liberty motors. The carrying capacity is 14 tons. The flight of 4513 miles was made in 55 hr. and 33 min.

even though they sink rapidly, appear to lose a part of their weight when submerged. For example, a man can lift a larger stone under water than he can lift in air. *The upward force any liquid exerts upon a body submerged in it is called its buoyancy.*

**37. Measure of Buoyancy. Archimedes' Principle.** A person in a bath-tub of water finds that he can support himself with very little effort by one hand placed upon the bottom of the tub. His body appears to have lost nearly all its weight in water. While at his bath, Archimedes, a Greek philosopher, observed the buoyant effect of the water upon his body; he discovered a method of finding the magnitude of this buoyancy. Suppose we are given a tub level full of water. Any body submerged in the tub would *displace* a volume of water equal to its own volume. If the body is weighed in air and then in water, the difference, or its loss of weight, is found to be exactly equal to the weight of water which overflows. Therefore the buoyant force of the water on the submerged body exactly equals the weight of water displaced. The principle of Archimedes may be stated as follows: *A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid it displaces.*

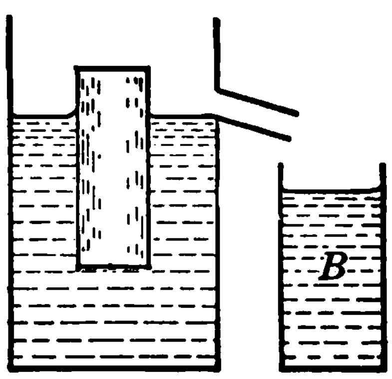


FIG. 25. — Overflow can and catch bucket.

Archimedes' principle may be demonstrated by the use of the apparatus shown in Fig. 25. The overflow can is filled with water up to the spout. A loaded block is weighed first in air and then in water. It is then carefully lowered into the overflow can. If the work is carefully done, the weight of the water which overflows will be exactly equal to the difference between the weight of the block in air and its weight in water.

**38. Explanation of Archimedes' Principle.** Suppose we submerge a cubical block 10 cm. on a side in water to such a

**Archimedes** (B.C. 287–212) was born in Syracuse, Sicily. His works on arithmetic, plane and solid geometry, and mechanics are still extant. He applied mathematics to the theory of such simple machines as the lever, the pulley, and the screw. Archimedes is best known through the principle that bears his name. Aided by the mechanical devices of Archimedes, Syracuse withstood a long siege. When the city was finally captured, Archimedes was killed by a Roman soldier.

**Blaise Pascal** (1623–1662) was a famous French philosopher. Pascal was also a noted author. In mathematics he wrote a treatise on conic sections. The physics student remembers him best for his research on fluid pressure, as summarised by Pascal's law. He carried out further experiments to verify Torricelli's conclusions concerning air pressure.

depth that its upper surface $A$ is 10 cm. below the surface of the water. See Fig. 26. The total *downward* force on the upper surface of the block equals area times depth times density, a total of 1000 gm. (Area = 100 sq. cm.; depth = 10 cm.) The total *upward* force on the surface $B$ equals 2000 gm. (Note that the depth is 20 cm.) The upward force exceeds the downward force by 1000 gm. Since the block has a volume of 1000 c.c. it must displace 1000 c.c., or 1000 gm. of water. Therefore the weight of the water displaced and the buoyant force are equal. The buoyant force is not increased by lowering the block deeper in the water, since each surface is lowered by the same amount, and the difference between the upward force and the downward force remains constant. Compute the buoyancy when the *upper* surface is 20 cm. below the surface of the water.

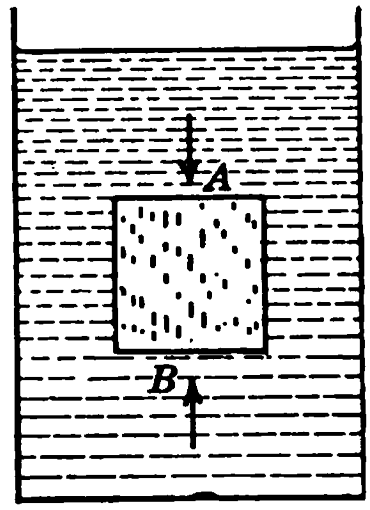



FIG. 26. — Buoyancy equals difference between upward and downward forces.

**39. Principles of Flotation.** A study of § 38 makes it easy to determine whether an object will float or sink in a given liquid, and if it floats, what fractional part of its volume will be submerged. Suppose the cubical block mentioned in the preceding paragraph weighs 1200 gm. in air. Immersed in water, the buoyant force is only 1000 gm. Hence an additional upward force of 200 gm. will be required to keep it from sinking.

Suppose, however, the block weighs in air only 800 gm. The buoyant force when the block is completely submerged is 1000 gm. In this case an additional downward force of 200 gm. would have to be applied to keep it submerged. In order to float it must displace 800 c.c. of water; hence it floats with 200 c.c., or $\frac{1}{5}$, of its volume above the water surface.

To summarize: (1) *A body sinks in a fluid, if the weight of the fluid it displaces is less than the weight of the body.*

FIG 27. — The U. S battleship New Mexico in Panama Canal. This s 32,000 tons of water. Her armor plates are 14 in. thick, and the turret armor is 18 in. thick. The electrically driven engines develop over 30,000 horse power, and drive the vessel 21 knots an hour. This battleship carries twelve 14-inch guns of 50 caliber (almost 60 ft. long). Such guns fire a projectile weighing 1400 lb. and have an effective range of more than 12 miles. The full complement of officers and men numbers more than 1500.

(2) *A submerged body remains in equilibrium, if the weight of the liquid it displaces exactly equals its own weight.*

(3) *If a body when submerged displaces a weight of fluid greater than its weight, it will rise and float with a part of its volume above the surface.*

**40. Applications of Archimedes' Principle.** The whole science of ship-building depends upon Archimedes' principle and the laws of flotation. A ship that weighs 4000 tons and carries a cargo of 8000 tons must be so proportioned as to length, breadth, and depth that it will displace 12,000 tons of water. Some of our largest battleships displace 32,000 tons of water. See Fig. 27. For every 64 lb. of weight an ocean vessel carries, one cu. ft. of sea-water must be displaced. The pontoon bridge, the floating dry-dock, and the submarine are all applications of these principles.

A person can float in salt water more easily than in fresh water, because the density of the salt water is slightly greater. The use of the ordinary life-preserver is an application of the third law of flotation. It adds but little to the weight of the wearer, but it increases his volume very greatly; hence the combination displaces more water. The various methods of finding the density of solids and liquids depend upon Archimedes' principle.

## *D.* DENSITY AND SPECIFIC WEIGHT

**41. Density and Specific Weight.** Density has already been defined as the weight per unit volume. In physics the word *specific* is frequently used and in each case it implies a ratio, or a comparison with some standard. *Specific weight, or specific density, may be defined as the ratio of the weight of unit volume of a substance to the weight of unit volume of some standard substance.* Water is the standard used for specific weights of solids and liquids. Specific weight is commonly called *specific gravity.*

Specific weight is an *abstract* number telling "how many times as heavy" a substance is as an equal volume of water.

In the Metric System both density and specific weight are numerically equal. *Example.* One c.c. of copper weighs 8.8 gm.; the *concrete* number, 8.8 gm. per c.c., equals the density of copper. The specific weight of copper = $\frac{\text{weight of 1 c.c. of copper}}{\text{weight of 1 c.c. of water}}$; the quotient is the abstract number 8.8, the same numerically as the density.

In the English system the density of copper is 549.12 lb. per cu. ft.; the density of water is 62.4 lb. per cu. ft. The specific weight of copper, 8.8, is a very different number from the density. In the English System, *density equals 62.4 times the specific weight.*

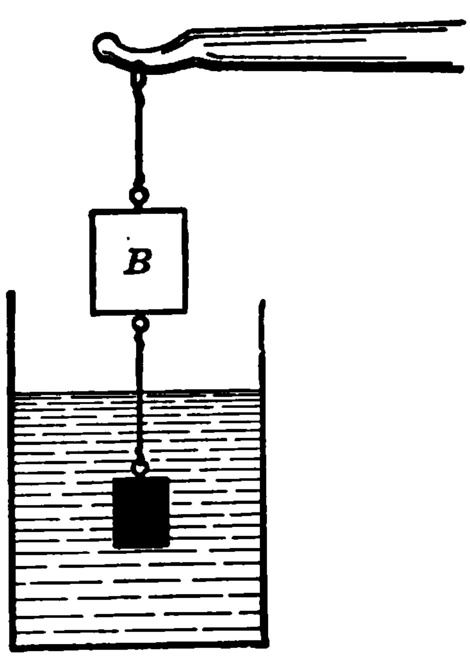



FIG. 28. — Specific weight of bodies lighter than water.

**42. Methods of Finding Specific Weight.** In general, finding the specific weight of an object requires three steps: (1) finding its weight; (2) finding its volume, either directly or indirectly; (3) dividing its weight by the weight of an equal volume of water.

(*a*) *Specific weight of a heavy solid.* To find the specific weight of a heavy solid insoluble in water we first weigh the solid in air; then we weigh it in water. The difference between the two weights, or the loss of weight in water, equals the weight of an equal volume of water. Therefore, the

$$\text{specific weight} = \frac{\text{weight in air}}{\text{loss of weight in water}}.$$

(*b*) *Specific weight of a solid lighter than water.* Since the solid is lighter than water, a sinker must be attached to submerge it. First weigh the solid in air and call its weight $w$; then find the combined weight, solid in air and sinker

in water, as in Fig. 28, calling this weight $w'$; next we find the combined weight when both the solid and sinker are submerged, calling the weight $w''$. The difference between $w'$ and $w''$ equals the buoyant force on the solid alone, or the weight of a volume of water equal to the volume of the solid. Therefore, the specific weight $= \frac{w}{w' - w''}$.

EXAMPLE. A piece of cork weighs 40 gm. A sinker immersed in water weighs 200 gm. The combined weight of the cork and sinker when submerged is 40 gm. Find the specific weight of the cork.

*Solution.* Sp. wt. $= \frac{w}{w' - w''}$. The weight of an equal volume of water is found by subtracting 40, the weight of both when submerged, from 240, the combined weight of cork in air and sinker in water. Then $40 \div 200$ equals 0.2, the specific weight of the cork.

(*c*) *Specific weight of liquids.* (*Bottle method.*) A small flask or bottle like that shown in Fig. 29 is very convenient for finding the specific weight of liquids. We first find the weight of the bottle; next we obtain the weight of the bottle when filled with water. The difference equals the weight of water the bottle can hold. In the same way we find what weight of liquid of unknown specific weight the bottle holds. Sp. wt. $= \frac{\text{weight of } x \text{ liquid}}{\text{weight of water}}$.

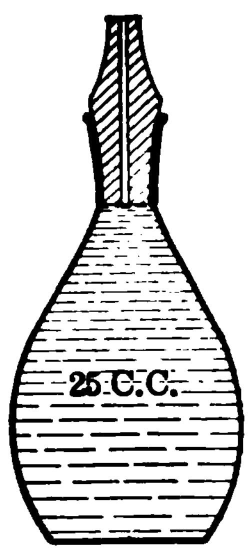


FIG. 29. — Pycnometer.

EXAMPLE. A small bottle weighs 22 gm.; filled with water it weighs 72 gm.; filled with alcohol it weighs 62 gm. Find the specific weight of the alcohol.

*Solution.* The bottle holds 50 gm. of water. It holds 40 gm. of alcohol. The specific weight of alcohol equals $\frac{40}{50}$, or 0.8.

(*d*) *Specific weight of liquids.* (*Loss of weight method.*) The denser a liquid, the greater its buoyancy. Hence we

may find the specific weight of a liquid by comparing its buoyancy with the buoyancy of water. A bulb, usually of glass or platinum, is weighed in air, then in water, and finally in the liquid whose specific weight is to be determined.

$$\text{The specific weight} = \frac{\text{loss of weight in } x \text{ liquid}}{\text{loss of weight in water}}.$$

EXAMPLE. A ball weighs 40 gm. in air, 32 gm. in water, and 28 gm. in a liquid of unknown density. Find the specific weight of the liquid.

*Solution.* Loss of weight in $x$ liquid is 12 gm.; the loss of weight in water is 8 gm. The buoyancy of the $x$ liquid compared with the buoyancy of water is $\frac{12}{8}$ or 1.5. Therefore the specific weight of the liquid is 1.5.

(*e*) *Specific weight of liquids.* (*Hydrometer method.*) A wooden rod, loaded at one end so it will float vertically, sinks in water until the weight of the water it displaces exactly equals its own weight. Placed in a liquid of unknown specific weight it sinks until the weight of $x$ liquid displaced equals its own weight. If the rod is uniform, the relative volumes of liquids displaced will be proportional to the depths to which the rod sinks. For example, if the rod sinks 10 cm. in water and to a depth of 8 cm. in $x$ liquid, then $x$ liquid is $\frac{10}{8}$, or 1.25 times as heavy as water.

FIG. 30 — Hydrometer.

$$\text{Sp. wt.} = \frac{\text{depth rod sinks in water}}{\text{depth rod sinks in } x \text{ liquid}}.$$

The *commercial hydrometer*, Fig. 30, has a scale so graduated that the specific weight of the liquid in which it floats may be read directly. The upper bulb is designed to increase the volume of the hydrometer, while the lower bulb is filled with shot or mercury so the vertical position of the hydrometer will be maintained as it floats.

Since the specific weight of liquids varies with their purity or concentration, the hydrometer is extensively used. The common acids are heavier than water. When diluted with water the mixture is less dense than the more concentrated acid. The ordinary hydrometer, or a special hydrometer called an *acidimeter*, may be used to test the concentration of acids. An *alcoholometer* is a special hydrometer used to determine the percentage of alcohol in a mixture of alcohol and water. The *lactometer* is a special hydrometer used to indicate the presence of added water in milk.

## SUMMARY

Liquids have weight; therefore they exert pressure on the bottom and sides of the containing vessel. Liquid pressure is proportional to the depth and density of the liquid; it is independent of direction.

The total force exerted upon any surface by a liquid equals the product of the area times the average depth times the density.

Pressure applied to any part of a confined fluid is transmitted so as to act with undiminished force in every direction. Such pressure acts with equal force upon equal areas. This principle is known as Pascal's law.

Pascal's law finds application in the hydraulic press and the hydraulic elevator. By sacrificing speed, a small force may be used to overcome a very great resistance. In all machines, acting force times the distance the acting force moves equals resisting force times the distance the resisting force moves.

The upward force a fluid exerts on a submerged body is called its buoyancy. Archimedes found that the magnitude of this buoyant force just equals the weight of the fluid displaced.

The buoyant force on a solid immersed in water must be *greater than* its weight, exactly *equal to* its weight, or *less than* its weight. In the first case the solid will rise to the surface and float with a part of its volume submerged. In the second case it remains in equilibrium in the liquid, and in the third case it sinks.

Density is the weight per unit volume. Specific weight is the weight per unit volume divided by the weight of unit volume of water.

## QUESTIONS AND PROBLEMS

1. A block of iron weighs 40 gm. in air and 34.8 gm. in water. Find the sp. wt. of iron. Find the weight of one cu. ft. of iron.

2. A wooden rod 12 in. long sinks in water to a depth of 9 in. Find its sp. wt. If it sinks in oil to a depth of 10.5 in., find the sp. wt. of the oil.

3. If ice has a sp. wt. of 0.92, find the weight of one cu. ft. of ice. Measure the inside of your ice-box, and compute the number of pounds of ice it will hold.

4. What is the meaning of the expression, "The specific weight of lead is 11.3"? What will 10 c.c. of lead weigh in air? In water?

5. A block of wood weighs 50 gm. in air; a sinker weighs 140 gm. in water; the combined weight of the wood and sinker in water is 120 gm. Find the sp. wt. of the wood.

6. Mercury has a sp. wt. of 13.6, and lead a sp. wt. of 11.3. What fractional part of a block of lead is submerged as it floats in mercury?

7. A flask weighs 30 gm.; filled with water it weighs 55 gm.; filled with chloroform it weighs 67.5 gm.; and filled with turpentine it weighs 52 gm. Find, (*a*) the volume of the flask; (*b*) the sp. wt. of the chloroform; and (*c*) the sp. wt. of the turpentine.

8. A cubical block of wood 10 cm. on a side floats in water. Its density is 0.7 gm. per c.c. Find (*a*) the volume of the block; (*b*) its weight; (*c*) what fractional part of the block is above the surface of the water; and (*d*) what force is required to sink it.

FIG. 31. — Floating dry-dock.

9. Given a large flat-boat, how could you use Archimedes' principle to find the weight of a locomotive?

10. Will the water line of a boat rise or fall as it goes from fresh water into salt water?

11. Hiero, tyrant of Syracuse, ordered a crown made of gold. He handed the crown to Archimedes, asking him to determine whether any other metal had been used in its construction. How did Archimedes solve the problem?

12. A floating dry-dock has 10 compartments. See Fig. 31.

Each compartment is 15 ft. wide by 15 ft. high by 1000 ft. long. How heavy a vessel can this dry-dock float?

**13.** A glass bulb weighs 60 gm. in air, 30 gm. in water, and 6 gm. in sulfuric acid. Find, (*a*) the volume of the bulb; (*b*) the sp. wt. of the bulb; and (*c*) the sp. wt. of the sulphuric acid.

**14.** A body weighs 40 gm. in air; its apparent weight when submerged in water is zero. Find its sp. wt. What is the sp. wt. of a body that loses half its weight in water?

**15.** A boy can lift 150 lb. If a stone has a sp. wt. of 3, how many cu. ft. of stone can he lift? How many cu. ft. of stone can he lift to the surface of a pond?

**16.** A cube of iron 10 cm. on a side has a sp. wt. of 7.6. Find its weight in air, and its apparent weight in alcohol of density 0.8 gm. per c.c.

**17.** A block of paraffin weighs 40 gm. in air. A sinker weighs 215 gm. in water. Both paraffin and sinker weigh 211 gm. in water. Find the sp. wt. of the paraffin.

**18.** A flatboat is 40 ft. long and 20 ft. wide. How much deeper will the boat sink in water when a load of 25 tons is placed on board?

**19.** A cake of ice is 5 ft. square and 18 in. thick. If ice has a sp. wt. of 0.92, what part of its thickness will float above the surface? If a man weighing 156 lb. steps on this cake of ice, what part of its thickness will be submerged?

**20.** Why does a battleship float when it is covered with steel plates 10 to 18 in. thick?

*Suggested Topics.* New York's High Pressure Water System. Irrigation Dams. How Your City Gets Its Water. Croton Aqueduct. Hydraulic Elevators, with cable, or with Horizontal Plunger.

## CHAPTER 3

# MECHANICS OF GASES. THE ATMOSPHERE

### A. THE ATMOSPHERE

**43. Air Has Weight.** The expression "light as air" is used so frequently that one is apt to get the idea that air has no weight or that its weight is negligible. The following simple experiment shows that the weight of air is appreciable. Find the weight of a glass bulb fitted with a stop-cock. See Fig. 32. Pump the air out of the bulb, close the stop-cock, and weigh it again. Its weight will be less than before. Or we may weigh an electric light bulb, which is practically a vacuum. When a hole has been made in the bulb by directing the tip of a blowpipe flame against one side, the air rushes in, and the bulb shows an increase in weight. Careful experiments show that *one liter of air at a temperature of 0° C. and under a pressure of one atmosphere, or 76 cm. of mercury, weighs 1.293 gm.* It is about $\frac{1}{773}$ as heavy as an equal volume of water.

FIG. 32. — Baroscope globe.

Although air is light when compared to water, yet in any considerable quantity the weight of air becomes an important factor. One cubic foot of air weighs a trifle more than $1\frac{1}{4}$ oz., and 1 cu. yd. a little more than 2 lb. The air in a room 18 by 18 by 12 ft. weighs a little more than 300 lb.

Air is the *popular* standard for determining the specific weight of gases, although hydrogen is a more scientific

standard. Hydrogen is the lightest gas known, and when it is taken as unity no gas can have a specific weight less than one. Some gases are several times as heavy as air, while several of them are slightly lighter.

**44. Air Exerts Pressure.** If we tie a thin rubber membrane over a bladder glass, as in Fig. 33, and then exhaust the air by means of an air pump, the rubber is forced down into the glass, and it will probably burst. Exhausting the air removes the *upward* air pressure, leaving an unbalanced *downward* pressure.

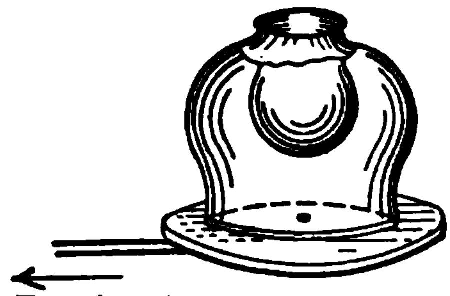


FIG. 33. — Air exerts pressure.

We may also use an empty varnish can to show air pressure. Let us take a can of one half gallon capacity, put in a little water, and then heat the water to boiling. The steam that forms drives all the air out of the can. Next let us stopper the can tightly and cool it by holding it under running water. As the steam condenses and produces a vacuum inside, the unbalanced outside pressure crushes the can. Since all gases have weight, they exert pressure. Like liquids, gases are fluid, although they are more mobile; their elasticity is almost perfect. Therefore, the facts we have already learned concerning liquid pressure and the principle of Archimedes apply to gases as well as to liquids.

Although we really live at the bottom of an "ocean of air," we do not feel the pressure which the atmosphere exerts, because the pressure is nearly equal in all directions. When we see the wind breaking the limbs of trees, uprooting trees bodily, or toppling over buildings, then we begin to realize the enormous pressure which the air can exert.

**45. Liquids Rise in Exhausted Tubes.** Every time we suck soda water through a straw we demonstrate the fact

that liquids rise in exhausted tubes. The Greeks and Romans explained this phenomenon by saying that "Nature abhors a vacuum," the liquid rising to take the place of the air which is removed by suction.

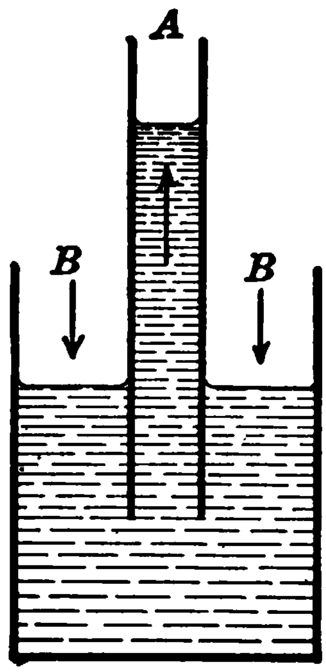


FIG. 34.—Liquids rise in exhausted tubes.

The Duke of Tuscany found that water would not rise more than 32 feet in a pump he was using. When he asked Galileo for an explanation, the aged philosopher replied that evidently "Nature's horror of a vacuum does not extend beyond 32 feet."

Galileo knew that air has weight and probably suspected that the pressure of the atmosphere causes liquids to rise in exhausted tubes. See Fig. 34. He devised an experiment to explain this phenomenon, but his death in 1642 occurred before he had time to complete his experiment. Torricelli, his pupil, continued the experiment and learned why liquids rise in exhausted tubes.

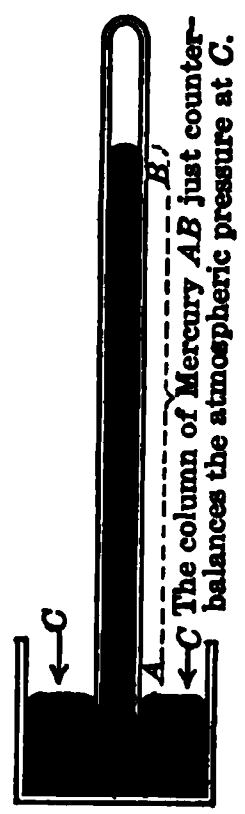


FIG. 35.—Torricelli's apparatus.

**46. Torricelli's Experiment.** In showing why liquids rise in exhausted tubes, Torricelli also found a method of measuring the atmospheric pressure. His experiment may be easily repeated. Take a glass tube about three feet long, closed at one end, fill it with mercury, place the thumb over the open end, and invert the tube in a bowl of mercury. See Fig. 35. Upon removing the thumb, the mercury in the tube, *ab*, stands at a considerable height above the level of the mercury in the bowl. The pressure of the air upon the surface of the mercury in the bowl is just counterbalanced by the weight of the mercury column, *ab*, which at sea-level is about 30 in. long.

**47. Pascal's Experiment.** Pascal reasoned that, if the mercury column in a Torricellian tube is sustained by the atmospheric pressure, the height at which such a column stands would be less at higher altitudes than at sea-level. He carried a Torricellian apparatus to the top of a tower in Paris and found a slight decrease in the height of the mercury column. Then he wrote to his brother-in-law, requesting him to repeat the experiment by carrying a Torricellian apparatus to the top of Puy de Dôme, a mountain about 1000 meters high. The mercury in the tube fell about 8 cm. as he made the ascent. Just as water pressure increases with the depth, so the air pressure is greater in valleys than it is on mountain tops.

**48. Magnitude of the Atmospheric Pressure.** The experiments begun by Torricelli and elaborated by Pascal prove conclusively that the height to which a liquid will rise in an exhausted tube depends entirely upon the pressure of the air on the surface of the liquid outside the tube. The average of a large number of experiments shows that the air at sea-level exerts a pressure sufficient to counterbalance a mercury column 76 cm. high (about 30 in.). A column of mercury 1 sq. cm. in cross-sectional area and 76 cm. high exerts a pressure of 76 times 13.6 gm., or 1033.6 grams. A column of mercury 1 sq. in. in cross-section and 30 in. high exerts a pressure of 14.7 lb.

Therefore the average pressure of the atmosphere at sea-level is 14.7 lb. per sq. in. The term "pressure of one atmosphere," is used a great deal in physics. It corresponds to 14.7 lb. per square inch, or 1033.6 gm. per sq. cm.

Since mercury has a specific weight of 13.6, it would take a column of water 13.6 times 30 in., or 34 ft., to counterbalance the atmospheric pressure. If the atmosphere exerts only enough pressure at sea-level to raise a column of water 34 ft., we can readily understand why the Duke of Tuscany's

pump would not lift water more than 32 ft., since no pump produces a perfect vacuum.

**49. The Magdeburg Hemispheres.** Otto von Guericke, mayor of Magdeburg, performed in the presence of the Emperor and the Reichstag a very striking experiment to show the magnitude of atmospheric pressure. He made two hollow hemispheres, about 22 in. in diameter; the edges were ground so smooth that when covered with a heavy grease and placed together they fitted air-tight. After the air was exhausted and the stop-cock closed, it is said to have required 16 horses to pull the hemispheres apart. Fig. 36.

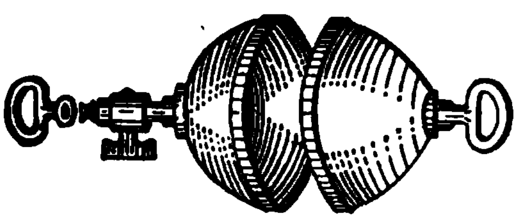


Fig. 36. — Magdeburg hemispheres.

**50. The Mercurial Barometer.** The ordinary mercurial barometer consists of a Torricellian tube and bowl, both inclosed in a metal frame or mounted on a board; a tube so mounted can be moved from place to place, and the height of the mercury column can be accurately measured. Mercury is suitable for use in such barometers since it is a very dense liquid and it does not freeze readily. Since it expands when the temperature is increased, the height of the mercury column must be corrected for temperature.

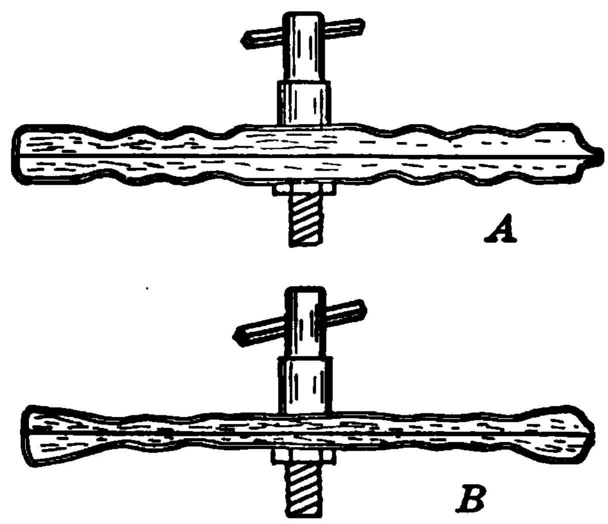



Fig. 37. — *A*. Corrugated box for aneroid barometer, partially exhausted. *B*. Corrugated box flattened by air pressure.

**51. The Aneroid Barometer.** The *aneroid* (without liquid) barometer consists essentially of a shallow box having a thin corrugated metal cover. Fig. 37. Since this box is a partial vacuum, the *elastic* cover is very sensitive to changes in atmospheric pressure. As it rises or falls in

response to pressure changes, its motion is communicated by delicate levers and a chain to a pointer that moves over a graduated scale. This scale is calibrated by comparison with a mercurial barometer. Fig. 38.

The aneroid barometer may be of practically any size. Some are small enough to be carried in the pocket like a watch. Many of them are about the size of an ordinary

FIG. 38. — Aneroid barometer.

alarm clock. A good aneroid barometer is so sensitive that it shows a change of pressure when lowered from a table to the floor. It is a very practical portable instrument.

**52. Uses of the Barometer.** (*a*) *To measure altitudes.* For many years the barometer has been used to determine altitudes. It is now more extensively used than before, since the determination of altitudes is of so much importance to aviators and balloonists. For comparatively small elevations, the barometer falls 0.1 of an inch for every 90 ft. of ascent. The fall is not quite so regular above a few hundred feet. Aneroid barometers for use on airplanes are grad-

uated to read altitudes directly. They are called *altimeters.*

(*b*) The barometer is also used for *forecasting weather.* Experiment shows that one cubic foot of *dry* air is heavier than one cubic foot of *moist* air. Hence the more moisture the air contains the less pressure it exerts. This fact is just contrary to the popular belief that moist air is heavy; it is often oppressive, but it is really lighter than dry air.

FIG. 39. — Barograph, or self-recording barometer.

From a single reading of the barometer, however, it is impossible to make any accurate predictions concerning weather conditions. Fig. 39 shows a self-recording barometer, or barograph. By observing *successive* readings of the barometer, some success in forecasting weather conditions may be attained.

A rising barometer shows that the air is becoming heavier; *hence a rising barometer indicates fair or clearing weather.*

*A rapidly falling barometer indicates an approaching storm.*

*Continued high barometer indicates steady, fair weather.*

**53. United States Weather Maps.** We have seen that some idea of future weather conditions may be gained by observing

successive barometer readings. Very much better results can be obtained by studying the readings of a number of barometers scattered over a wide area. The United States Government has observers stationed at various points throughout the United States. Reports taken simultaneously are telegraphed to central stations, where weather maps are prepared as follows: On a blank map of the United States heavy lines called *isobars* are drawn through places having

Fig. 40. — Weather Map of United States.

the same barometric pressure. Dotted lines called *isotherms* are drawn through places having the same temperature. From the map shown in Fig. 40, we see that Illinois is the center of a "low" barometer area. Just as water flows from high pressure to low pressure, or runs downhill, so winds blow from regions of high barometric pressure to low pressure areas. In general, *winds blow toward low pressure areas, but the rotation of the earth on its axis deflects the winds so that the storm has a rotary motion.* The winds in such *cyclonic* storms blow in a *counterclockwise* direction in the

northern hemisphere. They are accompanied by cloudy or rainy weather, with temperatures somewhat above normal.

From areas of high pressure, like that shown around Montana, the winds blow outward. The motion is also rotary, but *clockwise* in direction in the northern hemisphere. These *anti-cyclonic* storms are accompanied by fair or clear weather, with temperatures below normal.

From long periods of observation several facts concerning these storms have been established: (1) Cyclonic and anti-cyclonic storms travel in an easterly direction across the United States; (2) their velocity is from 400 to 700 mi. in 24 hr.; (3) as they pass successively over places at two- or three-day intervals, they bring with them the characteristic weather conditions already noted. Thus, a trained observer at a central station with all the data before him can make a fairly accurate estimate of the weather conditions to be expected.

**54. Height of the Atmosphere.** Just how high the atmosphere extends nobody knows. At an elevation of three miles the atmospheric pressure is only about one half as great as at sea-level. September 28, 1921, Lieutenant Macready ascended in an airplane at Dayton, Ohio, to a height of 37,800 feet. At such altitudes the air is too rare to support respiration, and aviators must carry oxygen tanks. Lieutenant Macready's fur suit was electrically heated, since the temperature falls to about $-70°$ F. It was necessary to supply the engine with compressed air to keep it working properly. Self-registering instruments have been carried in small balloons to a height of nearly 22 miles. At high altitudes the balloons burst and release the instruments, which are protected by parachutes against injury from rapid fall.

From the darkening of the moon by the earth's atmosphere at the beginning of an eclipse, from the height of the aurora borealis, and from observations of the height at which meteors

entering our atmosphere begin to glow, it is estimated that rarefied portions of the atmosphere extend to a height of from 125 to 500 miles.

## QUESTIONS AND PROBLEMS

1. Why must a mercurial barometer be hung in a vertical position? What would be the effect of inclining a barometer?

2. Exhaust the air from a bottle fitted with a stop-cock, as shown in Fig. 41. When the end of the tube is held under water and the stop-cock opened, water flows rapidly into the bottle. Explain.

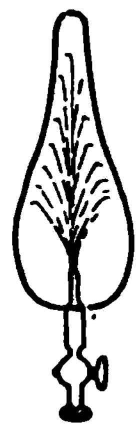


FIG. 41. — Fountain in vacuum.

3. Fill a bottle with water, cover it with a glass plate, and invert it in water. See Fig. 42. Why does not the water flow out when the glass plate is removed? Put one end of a glass tube under the mouth of the bottle and blow through the tube. Why does the air rise in the bottle? How is the water forced out of the bottle? Gases are often collected in this manner, the method being known as "water displacement."

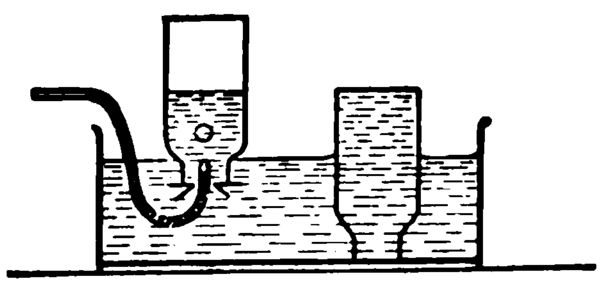


FIG. 42. — Gases are often collected by water displacement.

4. The ink-well shown in Fig. 43 is filled when it stands in the position shown at *a*. Why does not the ink flow out when the ink-well is in the position shown at *b*?

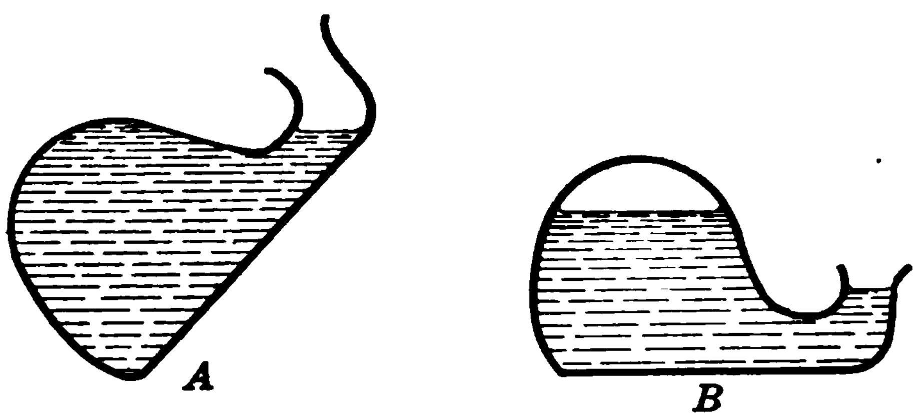



FIG. 43. — Pneumatic ink-well.

5. Liquids do not flow readily from a tap at the end of a barrel unless the bung is removed. Explain.

6. A person wishing to pour condensed milk from a can usually punches two holes in the top, at opposite sides. Why is the second hole necessary?

7. The cap of a fountain pen usually has one or more holes in it. Explain their purpose.

8. Pipettes are used in measuring liquids. As the air is sucked out of the pipette when its tip is beneath the surface of the liquid, the liquid rises in the pipette. Explain. If a finger is held tightly over the top, the liquid does not flow out even when the tip is raised above the surface. Explain. See Fig. 44.

FIG. 44. — Pipette.

9. Compare the action of a pipette with that of a medicine dropper or fountain-pen filler.

10. If water were to be used in constructing a barometer, how long a tube would be needed? State two reasons why mercury is suitable for use in barometers.

11. A barometer at the base of a cliff reads 29.8 in. At the top of the cliff it reads 29.1 in. What is the height of the cliff?

12. If a barometer were sunk in water until the surface of the bowl is 27.2 in. below the surface of the water, how would the barometer reading be affected?

13. Find the weight of the air in a room 40 ft. long, 30 ft. wide, and 16 ft. high.

14. What force did each team of horses exert to separate the hemispheres used by Von Guericke? (Compute the air pressure on an area 22 inches in diameter.)

15. Explain why hollow bodies are not crushed by the pressure of the atmosphere.

16. What would happen if a small pin-hole were made in the top of a barometer?

17. The first barometer constructed was a water barometer. The bowl was in the cellar and the tube extended up through the house above the roof. A wooden figure floating on the water rose above the roof in fair weather and retreated into the attic in foul weather. The owner was quite successful in forecasting the weather and was compelled to destroy his barometer because his neighbors accused him of wizardry. State the advantages of a water barometer and also give its defects.

18. A few years ago some workmen used steam to clean the interior of a tank-car. The opening was then tightly closed. A few minutes later, the steel car collapsed. Explain.

### *B.* COMPRESSIBILITY AND EXPANSIBILITY OF GASES

**55. Expansibility of Gases.** Solids and liquids have a definite volume, but gases expand and fill the vessel in which they are placed. The space they occupy depends upon the pressure to which they are subjected. A half-inflated rubber ball under a bell-jar expands as the air is pumped out of the jar, since the pressure on the ball is reduced. See Fig. 45. Since gases expand when heated and also when the pressure is reduced, it is necessary when measuring gas volumes to consider both the temperature and the pressure to which they are subjected. To prevent confusion, 0° C. and 760 mm. pressure are accepted as standard. When we refer to a volume of gas that measures 1000 c.c. at standard temperature and pressure (S.T.P.), we mean that when the temperature of the gas is 0° C. and the pressure upon it is equal to 760 mm. of mercury, or one atmosphere, its volume measures 1000 c.c.

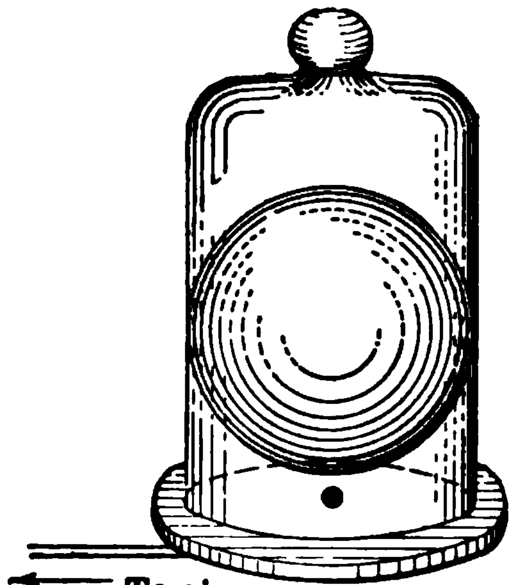



FIG. 45. — Gases expand when pressure upon them is decreased.

**56. Compressibility of Gases.** Gases differ from liquids in respect to compressibility. Water is so nearly incompressible that the stupendous pressure of 20 tons upon one cubic inch is required to reduce its volume by only $\frac{1}{10}$. On the other hand, a pressure of only 14.7 lb. per sq. in. reduces the volume of a gas at standard pressure to one half. Under a high pressure several "atmospheres" may be crowded into a container.

**57. Boyle's Law.** In studying the effect of varying pressures upon gas volumes, Robert Boyle found that gases are quite as elastic as a rubber ball or a coiled spring. When pressure is increased the volume decreases, but the gas expands to its original volume when the pressure is removed.

His experiments showed *that a given volume of dry gas, the temperature remaining constant, varies inversely with the pressure sustained by it.* Doubling the pressure reduces the volume to one half; tripling the pressure reduces the volume to one third.

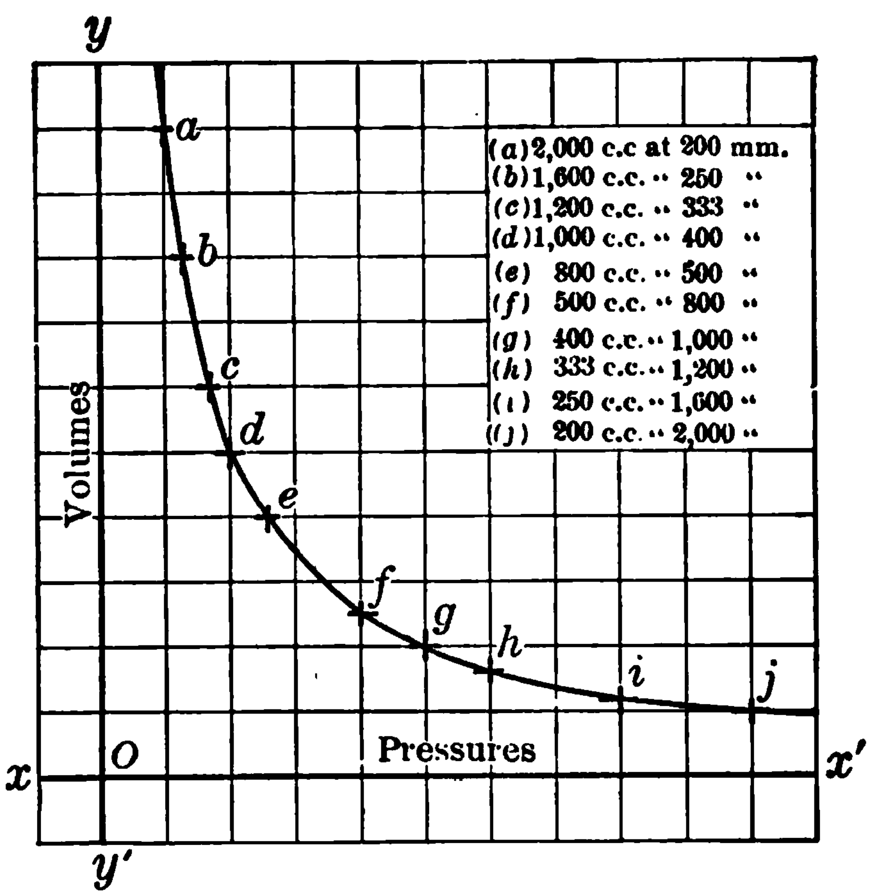



FIG. 46. — Curve of inverse proportion.

Fig. 46 shows a *curve of inverse proportion.* It shows how a given volume of gas, 2000 c.c., at a pressure of 200 mm., behaves when subjected to the various pressures recorded along the margin of the curve. Since one factor increases as the other decreases, *the product of the volume times the corresponding pressure is always a constant quantity.* Stated algebraically, $VP$ = a constant. The original volume times the original pressure equals the new volume times the new pressure. By formula, $VP = V'P'$.

Since there is no change in weight during the changes in gas volumes, evidently *the density of a gas increases in direct proportion to the pressure it sustains.* A box that holds 0.3 gm. of a given gas under a pressure of one atmosphere will hold 1.2 gm. under a pressure of four atmospheres.

PROBLEM. Given 450 c.c. of gas under a pressure of 745 mm. of mercury. What volume will the gas occupy at a pressure of 780 mm.?

*Solution.* Since the pressure is increased, evidently the volume will be reduced. The new volume will be $\frac{745}{780}$ of the original volume. $\frac{745}{780}$ of 450 c.c. equals 429.8 c.c., the volume under a pressure

of 780 mm. of mercury. Or, $VP = V'P'$. Then $450 \times 745 = V' \times 780$. Whence, $V' = 429.8$ c.c.

**58. The Air Pump.** The ordinary exhaust pump, of which a common type is shown in Fig. 47, is used to pump air from vessels, or to produce a partial vacuum. When the pump is in action the piston $P$ moves up and down in

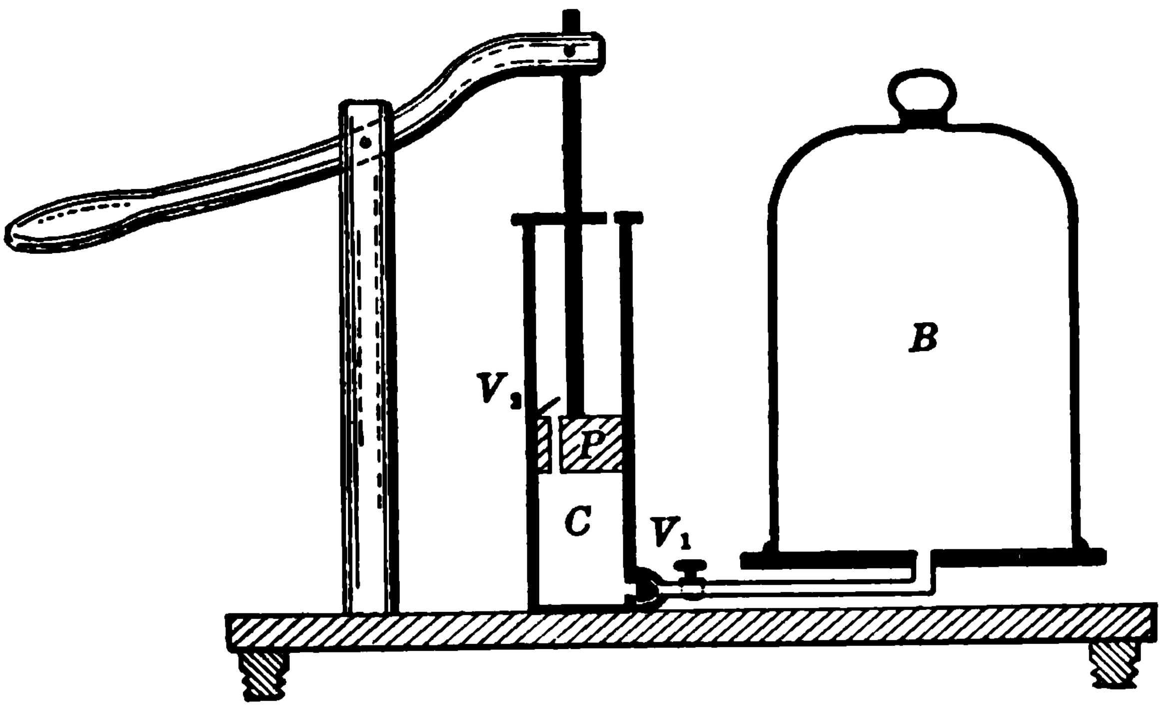



FIG. 47. — Exhaust air pump.

the cylinder $C$. This piston is practically air-tight. When it is raised, the valve $V_2$ being then closed, all the air above it is forced out through a hole in the top of the cylinder. The air in the bell-jar $B$ expands, part of it flowing over into the vacuum produced in the lower part of the cylinder. During the downstroke of the piston, the valve $V_1$ closes so the air cannot be forced back into the bell-jar. It passes up through valve $V_2$ into the upper part of the cylinder to be removed during the next stroke of the pump.

Suppose the cylinder and the bell-jar are both of the same size, one half the air will flow into the cylinder during the upward stroke of the piston, and one half of the air will be removed at the completion of one stroke of the pump. During the next complete stroke one half of the remaining air, or one fourth of the original amount, is removed. The next

stroke removes one half of what remains, or one eighth of the original amount. The action continues thus until the expansive force of the air finally becomes too weak to operate the valves of the pump.

**59. Aspirator.** Laboratory apparatus is often evacuated by the use of an aspirator, or suction pump. The aspirator, which is shown in diagram in Fig. 48, is screwed to a water faucet. As a current of water flows rapidly through the inner tube, it drags along with it the air molecules from the vessel to be exhausted. Quite a good vacuum can be produced in this way.

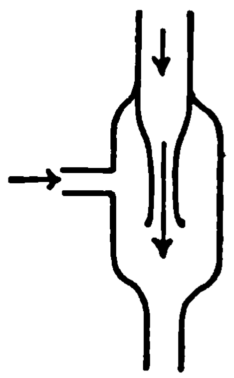


Fig. 48. — Aspirator.

**60. Ejectors and Injectors.** When the wind blows across the top of a chimney, the rapidly moving current of air carries along with it some of the air within the chimney, as shown in Fig. 49. For this reason a chimney draws much better on a windy day.

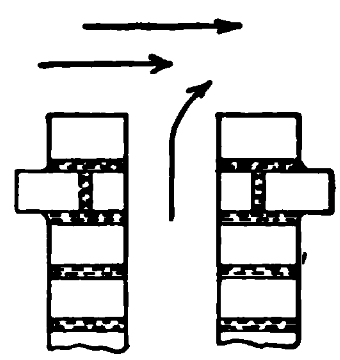


Fig. 49. — Ejector principle.

If we force a current of air across the open end of a tube which dips into a liquid, as in the atomizer of Fig. 50, we have another example of the ejector principle. The air pressure in the tube is lessened and the liquid is forced up the tube by the atmospheric pressure on the liquid in the bottle. At the tip of the tube the liquid is broken up into a fine spray by the current of air.

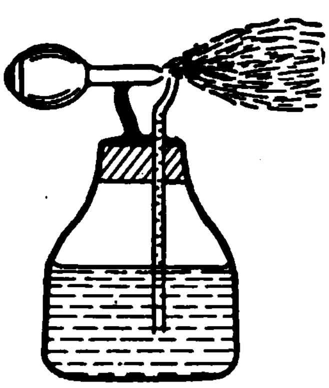


Fig. 50. — Atomizer.

The *injector*, which is sometimes used instead of a pump for filling steam boilers, does not differ in principle from the ejector. A blast of steam at high velocity flows through a jet surrounded by a nozzle. As the steam passes through the nozzle it carries water with it through a check valve into the boiler.

**61. The Compression Pump.** A compression pump is used to compress gases, or to crowd several atmospheres into a given volume. Fig. 51 shows the construction of one type of compression pump. As the piston, which fits the cylinder so perfectly that it is air-tight, is raised, air enters through the valve $V_1$, the valve $V_2$ remaining closed. On the downward stroke of the piston $V_1$ closes and the air is forced through $V_2$ into the container.

Such a compression pump may also be used as an exhaust pump. A vessel attached at $A$ is exhausted as the pump operates, while compression occurs in the container attached at $B$. Reversal of the direction in which the valves open converts a compression pump into an exhaust pump.

FIG. 51. — Compression air-pump.

**62. Uses of the Exhaust Pump.** In electric light bulbs, X-ray bulbs, thermos bottles, etc., a vacuum is necessary. Some type of exhaust pump is used for removing the air from such bulbs and bottles.

The *vacuum cleaner* also furnishes a practical application of the exhaust pump or exhaust fan. In the latter case a partial vacuum is produced by a fan driven by an electric motor. As the air rushes in through the mouthpiece of a tube leading to the fan chamber it carries with it the dust particles from the article that is being cleaned. A rotary brush sweeps and beats the rug or carpet at the same time, Fig. 52.

Since liquids evaporate more rapidly in a partial vacuum than under ordinary atmospheric pressure, *vacuum drying* is extensively used in many manufacturing plants. *Vacuum pans* are also used in sugar refineries, since the syrup boils

at a lower temperature under reduced pressure, and danger of scorching is avoided.

Fig. 52. — The revolving brush beats the rug gently and the dirt is pushed into the vacuum produced by the motor.

**63. Uses of Compression Pumps.** (*a*) *Pneumatic tires.* One of the most familiar applications of the compression pump is its use for inflating pneumatic tires. Several atmospheres are thus crowded into the tire. Since Pascal's law also applies to gases, air pressure is transmitted undiminished to every unit area of the container. Suppose air is forced into a tire under a pressure of five atmospheres. The outward pressure on each square inch of the tire wall becomes equal to 5 times 14.7 lb., or 73.5 lb.

(*b*) *The Westinghouse air-brake.* The air-brake may be operated directly from the engine or it may operate automatically from an auxiliary reservoir of compressed air stored under the car itself. In Fig. 53, *P* is a pipe connected with the main reservoir on the engine, in which a compressor maintains a pressure of about five atmospheres. The reservoir *R* communicates with *P* through a triple valve *V*. This valve maintains communication between *P* and *R* and shuts out the air

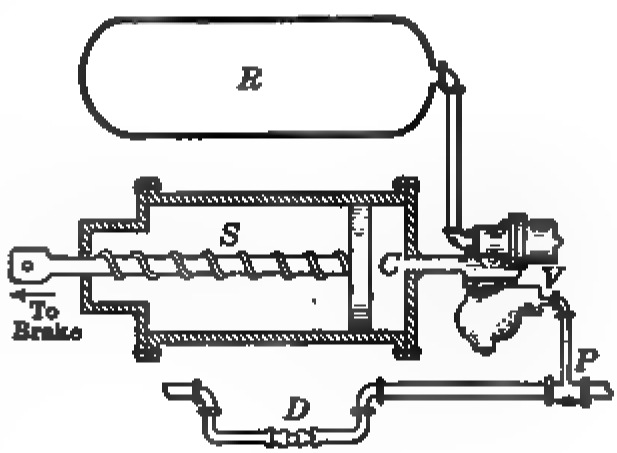


Fig. 53. — Westinghouse air-brake.

from $C$, as long as the pressure from the engine is supplied to $P$. When this pressure is diminished, either intentionally by the engineer or accidentally by the breaking of the coupling $D$, the valve opens in such a way that air from the reservoir $R$ flows into $C$ and forces the brake piston to the left, thus setting the brakeshoes against the wheels. Readmission of air through $P$ lets the air in $C$ escape and the spring $S$ releases the brakes.

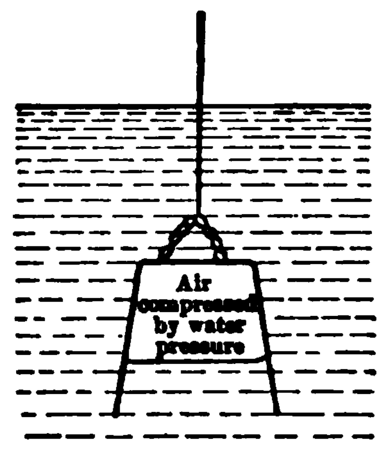


FIG. 54. — Diving bell being lowered.

(c) *Diving bells and diving suits.* If we force a tumbler under water mouth downward, the pressure of the water compresses the air in the tumbler to some extent, the amount of compression depending upon the depth. The air in a *diving bell* is compressed in a similar manner as it is lowered in the water. See Fig. 54. In the modern diving bell the workmen are supplied with air forced down through a tube connected with a compressor at the surface. The air is supplied fast enough to force all the water out of the bell and keep a stream of bubbles flowing out from its lower edges. See Fig. 55.

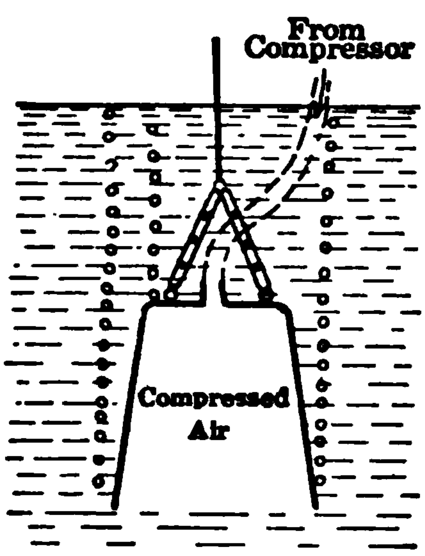


FIG. 55. — Diving bell supplied with compressed air.

The *diving suit* may be supplied with compressed air in the same manner, or the diver may carry at his back a tank of compressed air which he permits to escape fast enough to keep a constant stream of bubbles passing out through a valve in his suit.

The *pneumatic caisson*, which is used for constructing bridge piers or foundations under water, is supplied with compressed air in much the same manner as the diving bell.

(*d*) *Pneumatic despatch.* In some large buildings compressed air is used for transmitting cash boxes and small packages. It has also been used for transmitting mail between the post-office and the railroad stations, although the system threatens to yield to the motor truck. The cylindrical carrier, which is slightly smaller than the tube, has packing rings near the ends to make it fit the tube fairly tightly without much friction. An exhaust pump at the receiving end and a compression pump at the transmitting end of the tube produce a difference of pressure that is sufficient to drive the carrier through the tube with considerable speed.

(*e*) *Other uses for compressed air.* Many tools are operated by compressed air. The list includes *riveting hammers, rock-drills, the sand blast for cutting and polishing*, and *some*

FIG. 56.— Pneumatic riveter. (1) Valve controlling air; (2) hammer; (3) trigger.

*rotary tools.* See Fig. 56. The *bellows* are used to produce a forced draft for making a blacksmith's forge hotter, or to supply compressed air for organ pipes. They are indirectly used to produce the partial vacuum needed for the operation of player pianos.

Mines and large buildings are often ventilated by compressed air. It is used to operate car doors and for various regulating devices. In submarines it is used to force the water from the various chambers, and it operates the propellers which drive torpedoes.

## QUESTIONS AND PROBLEMS

1. Would air be suitable for use in a hydraulic press? Explain.

2. Theoretically, can a perfect vacuum be produced with a pump of the type described in § 58?

3. Suppose the piston of an air-brake has a diameter of 6 inches. What force acts to set the brakes if the air in the reservoir is under a pressure of five atmospheres? (Consider the effective pressure equal to four atmospheres. Why?)

4. A man needs a certain number of grams of oxygen daily. Why must he breathe more frequently at the top of Pike's Peak than at sea-level? Breathing mountain air exercises the lungs, and it is thus beneficial to consumptives.

5. A diver is submerged in water to a depth of 170 ft. To what total pressure, both atmospheric and liquid, is he subjected? How will the volume of a bubble of gas be affected as it rises from the valve of his suit to the surface of the water?

6. A certain volume of gas measures 1400 c.c. when the barometric reading is 825 mm. What volume will the gas occupy when the pressure is 645 mm.? What pressure is required to reduce the volume to 940 c.c.?

7. What will be the weight of one liter of air in a tire that is inflated under a pressure of 5 atmospheres?

8. The volume of a certain gas is 630 c.c. when the pressure is 96 cm. What pressure will be needed to reduce the volume to 410 c.c.?

### *C.* Other Pneumatic Appliances

**64. The Lift Pump.** The *lift*, or *suction* pump, Fig. 57, consists of a cylinder $C$, connected with a pipe which extends down into the well $W$. A piston $P$ is moved up and down in the cylinder by means of the pump-handle. As $P$ moves upward with valve $V_2$ closed, a partial vacuum is

Fig. 57. — Lift pump (for shallow wells).

produced in the cylinder and pipe just as in the upward stroke of the air pump. The downward pressure of the air upon the water surface forces some water up through the pipe into the cylinder. During the downward stroke of the piston, valve $V_1$ closes to prevent the return of the water, which passes through valve $V_2$. The next upward stroke lifts the water to the spout.

Since the atmospheric pressure balances a column of water only 34 ft. high, the suction pump cannot be used if the piston stands more than 34 ft. above the surface of the water. In practice, the height to which water can be raised by such a pump is generally about 28 ft., since leakage of the valves cannot be entirely eliminated.

**65. The Force Pump.** The force pump differs from the lift pump in two respects: (1) The piston is solid; (2) valve $V_2$ is not in the piston, but at the entrance to the outlet pipe near the bottom of the cylinder. See Fig. 58. The upward stroke of the piston produces a vacuum exactly as with the lift pump. During the downstroke valve $V_1$ closes and the water is forced into the outlet pipe $S$. Valve $V_2$ keeps it from flowing back into the cylinder during the next upstroke of the piston.

FIG. 58. — Force pump (for deep wells).

The water issues from the spout during the downstroke *only*, unless an air-dome is used. During each downstroke some water is forced into the air-dome $A$. The air in the dome is thus compressed, but its expansive force causes the water to flow from the spout while the upstroke is being completed. Thus the flow of water becomes quite continuous.

Since the cylinder can be put near the surface of the water, and the force exerted at the handle used to raise the water, a force pump can be used in deep wells where the use of a lift pump would be impractical.

**66. The Chain Pump.** We have represented in Fig. 59 an efficient pump which is extensively used for shallow wells and cisterns. *AC* is a wooden tube about three inches square through which a hole about $1\frac{1}{4}$ inches in diameter is bored lengthwise. When the ratchet wheel *W* is turned by a crank, a continuous chain is pulled up through the tube and lowered into the well on the other side of the wheel. Rubber buckets *B* which fit the pump tube air-tight are inserted in the chain at intervals of 6 or 8 ft. As a rubber bucket is pulled up through the pump-stock *AC* it removes the air, and the water follows, being lifted to the spout partially by atmospheric pressure and partially by the bucket that follows.

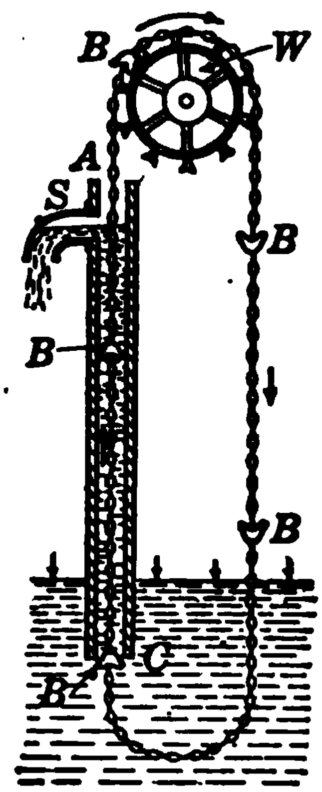


FIG. 59.— Chain pump.

**67. The Siphon.** The siphon consists of a bent tube with arms of unequal length. It is used for transferring liquids from one container to another of lower level. It is especially convenient for handling corrosive liquids, or in drawing liquids from large containers.

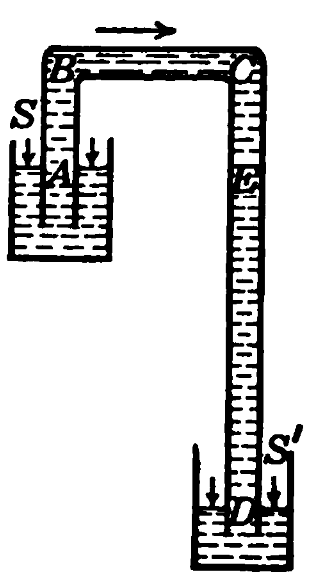


FIG. 60. — Siphon.

Suppose the tube *ABCD* is filled with liquid and its ends placed in the liquids at *S* and *S'*, Fig. 60. The atmospheric pressure at *S* supports the column of liquid *AB*; the atmospheric pressure at *S'* supports the column of liquid *CD*. At *S* the atmospheric pressure is reduced by the pressure of the liquid column *AB*. At *S'* the atmos-

pheric pressure is reduced still more by the pressure of the liquid column $CD$, which is longer than the column $AB$. The *effective* pressure of the atmosphere at $S$ therefore becomes greater than at $S'$, and the liquid is forced from $S$ into $S'$ through the tube $ABCD$.

Since the difference in the magnitude of the liquid pressures in the two arms really causes a siphon to flow, the rate at which it flows must increase as the difference in the lengths of the two arms becomes greater. Conversely, when this difference is reduced to zero, the siphon ceases to flow.

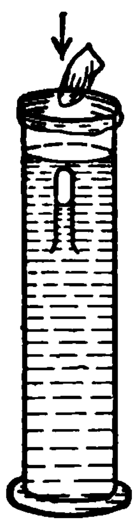


FIG. 61. — Cartesian diver.

**68. The Cartesian Diver.** By careful adjustment it is possible to put into a small vial just enough water so that the slightest downward force applied to it, as it floats mouth downward in a cylinder of water, will submerge it. See Fig. 61. If a piece of sheet rubber is stretched over the cylinder and pressure applied to it gradually, the vial slowly descends, rising again when the pressure is removed. The Cartesian diver, or bottle imp, illustrates several principles of physics. Before the pressure is applied, the specific weight of the vial and contents is slightly less than that of water. The pressure applied is transmitted equally in all directions (Pascal's law), the air in the vial is compressed, and a little more water enters the vial, thus increasing its specific weight until it slowly sinks. When the pressure is removed, the expansion of the air in the vial forces out some of the water and the vial rises. The *diver* is an application of Pascal's law, Archimedes' principle, the laws of flotation, and the compressibility and expansibility of air (Boyle's law). The usual type is a toy devised by Descartes. It consists of a hollow imp-shaped figure with a small opening in the end of his tail for the entrance and exit of the water which changes his specific weight.

**69. The Submarine.** The principle of the submarine is essentially the same as that of the Cartesian diver. When the submarine is to be submerged, certain compartments are opened to fill them with water. By this method the vessel is nearly submerged. It is then forced under water by the combined action of the propellers and horizontal diving rudders. It is brought to the surface again by the proper handling of the horizontal rudders. Compressed air is used to force the water out of the flooded compartments, Fig. 62.

**70. Buoyancy of Gases.** Since Archimedes' principle applies to all fluids, an object surrounded by a gas is buoyed up with a force equal to the weight of the gas displaced. An object that displaces 1 liter of air would weigh 1.293 gm. more in a vacuum than in air at S.T.P. In other words, the buoyancy of air is 1.293 gm. per liter. The laws of flotation also apply to gases; hence an object rises in air if the weight of the air it displaces is greater than its own weight.

**71. Balloons and Airships.** A balloon consists of a strong, air-tight bag filled with some gas lighter than air. It will rise in

FIG. 62. — Diagram of a submarine.

Fig. 63. — The R 34 was the first dirigible airship to cross the Atlantic Ocean. The flight from Scotland to Mineola, Long Island (3700 mi.), was made in 108 hr. The actual distance covered, however, was over 7000 mi., an average speed of 67 mi. per hr. The five 12-cylinder engines used develop nearly 1400 H.P. The R 34 was 672 ft. long, 90 ft. high, and 79 ft. in diameter. The 18 gas bags inside the duralumin frame had a capacity of 2,000,000 cu. ft. The R 34 carried 81 petrol tanks, which held 70 gallons each. (*Central News Photo*)

air if its weight plus the weight of the gas it contains is less than the weight of the air it displaces. If the balloon is filled with hydrogen, a gas which weighs 0.09 gm. per liter, then every liter of air the balloon displaces exerts a lifting force equal to the difference between the weight of a liter of air and a liter of hydrogen. Therefore *the so-called lifting force of hydrogen is 1.2 gm. per liter.* Coal gas weighs 0.75 gm. per liter; its lifting force is 0.54 gm. per liter. Coal gas is cheaper than hydrogen, but a balloon filled with coal gas could carry less than half the weight carried by the same balloon filled with hydrogen. Since there are 1000 liters in one cubic meter, the lifting force of gases may be expressed in kilograms per cubic meter.

Hydrogen is the lightest gas known, but it is very inflammable. During the World War, *helium* began to be used in military balloons. It is a light, non-inflammable gas twice as heavy as hydrogen. It is nearly 93% as efficient as hydrogen and all danger from fire is eliminated. Helium is found in some natural gas wells in Texas and Oklahoma. The gas is liquefied and the helium is separated from the liquid.

Since air is very compressible, the layers near the surface of the earth are compressed by the weight of the air they sustain, and their density is correspondingly increased. When a rising balloon enters a rarer atmosphere, the buoyant force gradually grows less. It will continue to rise until the weight of the balloon and its contents just equals the weight of the air displaced. If balloons were filled entirely full before starting, the unbalanced expansive force might tear the gas-bag when the balloon rises into a rarer atmosphere.

*Airships*, or *dirigibles*, are balloons fitted with steering devices and propellers. Several gasoline engines aggregating 4000 to 5000 horse power are used to drive the propellers of the huge military dirigibles, some of which measure nearly 700 ft. in length. See Fig. 63.

**72. Measurement of Gas Pressure.** The open mercury manometer and the spring gauge are both used to measure gas pressures. See § 30. The *closed mercury manometer* is also used. It is shorter than the open manometer and requires less mercury. When the mercury stands at the same level in both arms, the pressure is one atmosphere. See Fig. 64. When the pressure at $A$ is increased mercury is forced into $B$, compressing the air in the closed end of the tube (Boyle's law). The scale may be calibrated to read atmospheres directly. Engineers speak of a "27-in. vacuum" or a "28-in. vacuum" in referring to reduced pressures. A "28-in. vacuum" means a pressure 28 in. less than one atmosphere, which is 30 inches.

Fig. 64. — Closed manometer.

**73. The Gas Meter.** The gas meter is a metal box divided into four compartments by flexible diaphragms. By a slide valve these compartments are alternately connected with the city supply and with the pipe to the consumer. While the gas in one compartment is being used, the other compartment is being filled. See Fig. 65. The movement of the diaphragms not only operates the slide valve but it also controls a clock-work device which records the


Fig. 65. — A gas meter.

number of cubic feet of gas that passes through the meter. Fig. 66 shows the dials of a gas meter. An official of the company reads the meter monthly and determines the amount of gas used each month by subtracting successive readings. The dials in Fig. 66 indicate 59,300 cu. ft. When the needle stands between two numbers, as on the left-hand dial, the lower number is always taken as the reading.

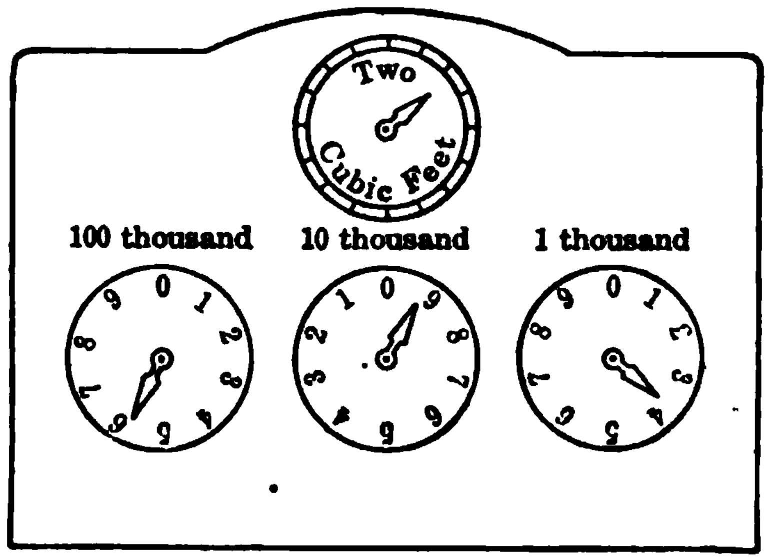


Fig. 66.— Dials of gas meter.

## SUMMARY

Air has weight. 1 liter of dry air at S.T.P. weighs 1.293 gm. Air also exerts pressure. At sea-level the pressure is 14.7 lb. per sq. in.

The rise of liquids in exhausted tubes is caused by air pressure. Torricelli showed that air pressure supports a column of mercury 76 cm. high. Pascal showed that air pressure decreases as the elevation is increased.

A barometer is an instrument used to measure atmospheric pressure. It is used to measure altitudes and in weather forecasting. A rising barometer indicates fair weather. A falling barometer indicates an approaching storm. A steady barometer indicates settled weather.

Unlike liquids, gases placed in a container expand and fill the container. Gases also differ from liquids from the fact that they are easily compressed.

Robert Boyle found that at constant temperature a given volume of dry gas varies inversely as the pressure sustained by it. The density of a gas increases with increased pressure.

Archimedes' principle applies to gases. The buoyant force a gas exerts is equal to the weight of the gas displaced.

Compressed air is used in pneumatic tires, diving bells, air-brakes, riveters, and drills.

## QUESTIONS AND PROBLEMS

1. Why is a small rubber balloon filled with hydrogen likely to burst after it has risen some distance?

2. When will a balloon stop rising?

3. If the total weight of a balloon is 1000 kgm., what must its minimum volume be if it is filled with hydrogen? How much larger must the balloon be if it is filled with helium?

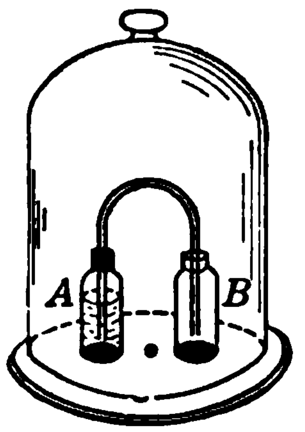



Fig. 67. — Bacchus' experiment.

4. Two small bottles are placed under a bell-jar. See Fig. 67. *A* is *partly* full of liquid and is tightly stoppered. When the air is pumped out of the bell-jar the liquid flows through the bent tube into *B*. When the air is again permitted to enter the jar, the liquid flows back into *A*. Explain. Repeat the experiment, having *A* *full* of liquid.

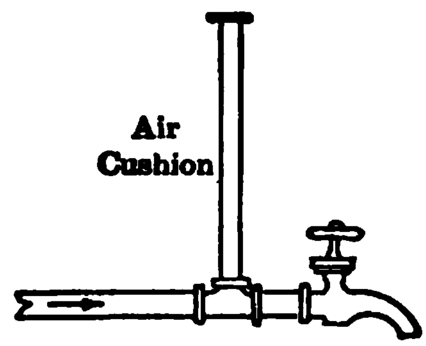



Fig. 68. — Air cushion prevents "pounding."

5. A pipe is sometimes fitted to the water pipe near the faucet, as shown in Fig. 68. How does such a pipe, which contains air, keep the water from "pounding," when the faucet is closed quickly?

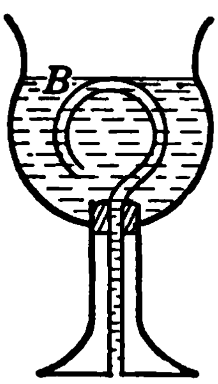



Fig. 69. — Intermittent siphon.

6. To what height must the siphon shown in Fig. 69 be filled before it begins to flow? How long will it continue to flow? To what height must the liquid rise to start the flow a second time?

7. Will a siphon flow if the short arm is more than 34 ft. long? Give a reason for your answer. Will it flow if the long arm is more than 34 ft.?

8. The *aspirating* siphon is used with corrosive liquids. Study Fig. 70, and then tell how you would fill such a siphon with liquid to start its action.

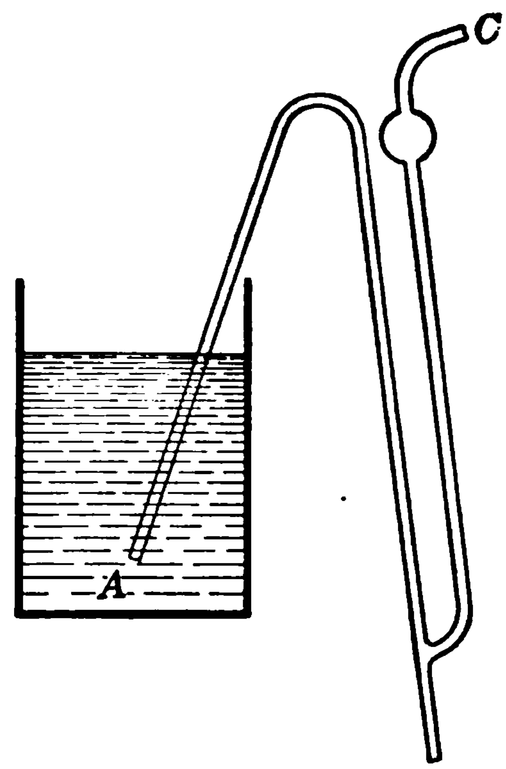



Fig. 70. — Aspirating siphon.

9. Why do both valves of a pump open upward? Why do they open alternately?

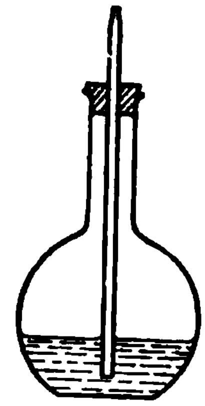


FIG. 71. — Blowing into flask compresses air.

10. Water is often poured into a lift pump to aid in starting it. Explain. (This operation is called "priming" the pump.)

11. A lift pump is to be used for pumping oil, sp. wt. 0.85. How high can the oil be lifted by a pump which is efficient enough to lift water 28 ft.?

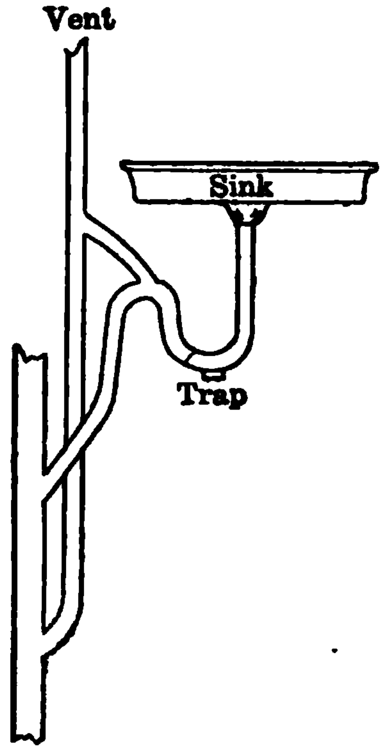



FIG. 72. — Trap for sinks.

12. If you use gas, take an independent reading of your meter on the same day it is read by the company official. Take a second reading one month later, and compute your gas bill for the month. Check your results with the statement sent by the gas company.

13. Does it indicate high or low atmospheric pressure when smoke rises vertically from a chimney? Is there truth in the old saying, "It is a sign of rain when the smoke falls to the ground"?

14. Blow through the jet tube shown in Fig. 71 as hard as you can. Explain the results.

15. What is the purpose of the trap in a sink or toilet, as shown in Fig. 72? Is it a siphon? If not, try to learn what prevents its acting as a siphon.

*Suggested Topics.* How Weather Maps Are Made. The Los Angeles Siphon. Compressed Air as a Motive Force. Mercury Air Pumps.

# CHAPTER 4

# MOLECULAR PHYSICS

## *A.* MOLECULAR MOTIONS

**74. Kinetic Theory of Matter.** In § 3, we learned that all matter is made up of exceedingly small particles called molecules. In gases especially, we know that the molecules are by no means relatively near neighbors. In liquids and solids they are crowded more closely, but in all cases there is sufficient space between adjacent molecules to permit the molecules to move freely. The word *kinetic* is derived from the Greek word *kinere*, which means *to move*. *The kinetic theory of matter assumes that the molecules of all matter are in constant motion.* The rate and nature of such motion depend upon the nature of the substance, its state, and its temperature. There are many evidences that tend to prove the correctness of the kinetic theory.

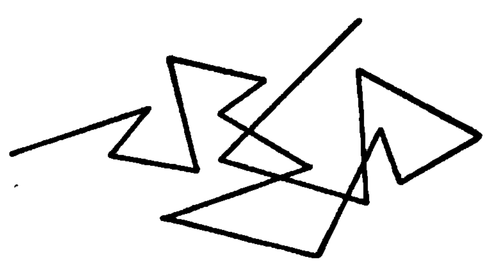


Fig. 73.—Path of moving particle.

The ultramicroscope shows that very small particles suspended in a liquid are never at rest. They move backward and forward, or dance up and down, in ceaseless motion. These Brownian movements are caused by the motion of the liquid molecules which by their impact drive the particles hither and thither. Minute oil drops suspended in air undergo the same zigzag motions as they are driven about by the rapidly moving air molecules. Fig. 73 shows a path taken by a moving particle.

### *B.* MOLECULAR MOTIONS IN GASES

**75. Expansion of Gases.** If a gas-cock is left open, in a few minutes the odor of gas may be detected in all parts of the room. If we unstopper a small bottle of chlorine gas in a large vessel of air, the yellowish green gas may be seen expanding and mixing with the air in the vessel. Evidently the molecules of these gases are in very rapid motion. The gas molecules move rapidly in all directions until they become thoroughly mixed with the air molecules. A little mustard gas or phosgene soon spreads to every part of a dugout. Air from the bell-glass, Fig. 47, expands instantly and fills the vacuum formed beneath the rising piston of the air-pump. If the molecules of gases were not in constant motion, it would be impossible to produce a vacuum with an air-pump. Thus the expansion of gases furnishes one proof of the motion of their molecules.

**76. Gases Exert Pressure.** Pneumatic tires frequently burst from the pressure which the air inside exerts on the walls of the tire. This pressure is due to the constant bombardment of the moving molecules. If we pump five atmospheres into the space formerly occupied by one atmosphere, there will be five times as many molecules bombarding the walls of the container, and the pressure will be five times as great. The driver of an automobile uses a small pressure gauge to measure the force exerted by the molecules upon each square inch of the inflated tire. By Pascal's law, the pressure is transmitted equally in all directions. If one spot in the tire is especially weak, a "blow-out" may occur. All the devices which utilize compressed air afford examples of gas pressure due to molecular motion. Steam in boilers often exerts a pressure of 200 lb. or more per sq. in. In this case it is also evident that the molecules are widely separated when compared with the diameters of the molecules themselves, for the water formed when steam condenses

occupies only about $\frac{1}{1600}$ the volume of the original steam. The high temperature increases the velocity of the steam molecules, and the rapidly moving molecules exert great pressure.

**77. Diffusion of Gases.** Hydrochloric acid is a water solution of a heavy gas, hydrogen chloride; aqua ammonia is a water solution of a light gas, ammonia. When these two gases unite, they form a cloud of fine white particles. Suppose we put a couple of drops of hydrochloric acid in a warm bottle, an equal amount of aqua ammonia in a second bottle, cover both with glass plates, and then invert the bottle containing ammonia over the acid bottle, as shown in Fig. 74. After the bottles have stood a few minutes, a vigorous action may be observed when we remove the glass plates. The ammonia gas moves downward and mixes with the heavy hydrogen chloride, and vice versa. Such *mixing of gases in apparent violation of the laws of weight is called diffusion.*

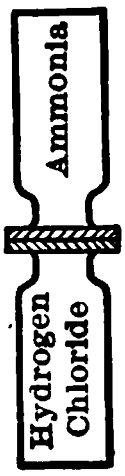



FIG. 74. — Gases mix by diffusion.

**78. Diffusion through Porous Solids.** In the apparatus shown in Fig. 75, an unglazed earthenware cup is closed with a rubber stopper carrying a glass tube which dips into some colored liquid. When a beaker is inverted over the cup and illuminating gas is led into the beaker, air begins to bubble out through the liquid. This experiment shows that gases diffuse through a porous solid. It also shows that the lighter molecules of illuminating gas move faster than the heavier air molecules. If a heavy gas like carbon dioxide is led into the beaker, then the air molecules flow out through the porous cup faster than the carbon dioxide

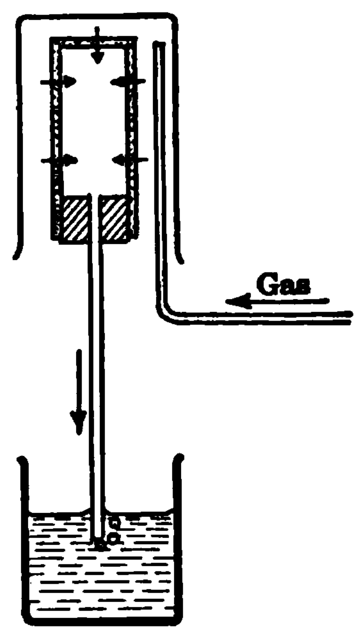



FIG. 75. — Gases diffuse through solids.

molecules enter. This reduces the pressure inside and the colored liquid rises in the tube.

*Diffusion of fluids through a plant or animal membrane is called osmosis.* It is very important in respiration. The oxygen of the air passes through the walls of the capillaries in the lungs and enters the blood.

### C. MOLECULAR MOTION IN LIQUIDS

**79. Evaporation.** Every one knows that water left standing in an open vessel soon disappears by evaporation. This is true of liquids in general, some evaporating more rapidly than water, and others more slowly. It is quite impossible to explain the disappearance of liquids by evaporation, unless we assume that the molecules of the liquid are in motion.

FIG. 76. — Diffusion of liquids.

**80. Diffusion of Liquids.** Liquids also mix by diffusion, although much more slowly than gases. If we pour through a thistle tube a concentrated solution of copper sulphate into a cylinder containing water, Fig. 76, the water will float on the surface of the heavier blue solution of copper sulphate, forming two distinct layers. A few days later the line of demarcation will be quite irregular, showing that diffusion is taking place. It may require weeks or months before the diffusion is complete, whereas the diffusion between the two gases discussed in § 77 was complete in a few minutes. The molecules of liquids move more slowly than the molecules of gases.

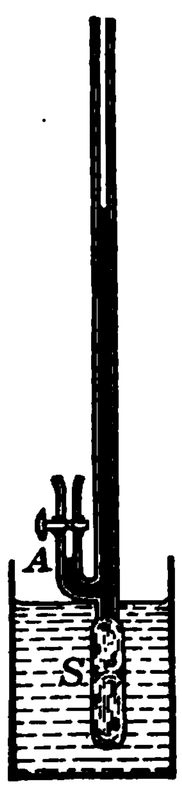



FIG. 77. — Osmosis of liquids.

**81. Osmosis in Liquids.** Osmosis occurs not only in gases but also in liquids. Fig. 77 shows an apparatus that is very convenient for showing that liquids diffuse through a membrane.

The diffusion shell $S$ and the tube are filled to the mark $A$ with a colored sugar solution of 1 or 2% strength. The shell is then immersed in a vessel of water. In a few minutes the liquid begins to rise in the tube, and by the following day it will probably have reached a height of several feet. The light water molecules move more rapidly than the sugar molecules and hence have greater penetrating power. Thus osmosis takes place readily from the less dense to the more dense liquid. The pressure produced by osmosis may equal several atmospheres.

Osmosis of liquids is quite as important as that of gases. The purpose of digestion is to render the food sufficiently fluid to be absorbed by osmosis. Each cell receives its nourishment by osmosis through the cell wall. Oysters are wrinkled when removed from sea-water. They may be "fattened" by floating them in fresh water. The osmosis is inward and the body wall is distended by the osmotic pressure.

### *D.* MOLECULAR MOTION IN SOLIDS

**82. Evaporation.** The fact that solids evaporate is not so well known, but a little thought must convince us that solids evaporate, although in most cases very slowly. A piece of musk will give off enough vapor to be perceived in any part of the room. A lump of camphor gum, or a crystal of iodine, will disappear in a short time by evaporation. Moth balls evaporate completely in time. Snow and ice evaporate quite readily. They disappear when it is too cold for them to melt. It is probable that many other solids evaporate, but so slowly that in many cases it is difficult to detect.

**83. Diffusion of Solids.** If a lead plate and one of gold are left in close contact for a long time, particles of gold may be detected throughout the lead, showing that solids slowly

diffuse. Other solids show a similar effect if the temperature is increased a few hundred degrees. From the evaporation and diffusion of solids it is evident that their molecules also accord with the kinetic theory.

### *E.* MOLECULAR FORCES

**84. Molecular Forces in Solids.** Since there is so much evidence in support of the kinetic theory, the student probably wonders why all substances do not evaporate and expand indefinitely. Instead we know that many solids have great tensile strength and that enormous forces are required to pull them apart. Evidently there is a strong force binding together the molecules of such tenacious solids. *The force of attraction between like molecules is called cohesion.*

*The force of attraction between unlike molecules is called adhesion.* Adhesion between unlike molecules holds a postage stamp to a letter. Crayon sticks to the blackboard and the graphite from a " lead " pencil sticks to paper because the adhesion of their molecules for the board or paper is greater than the cohesion between their molecules.

**85. Solids, Liquids, and Gases Compared.** Generally, the force of cohesion in solids is very great. The moving molecules are so firmly held by this force that they probably oscillate about fixed points, and do not change their relative positions to any marked degree.

In such liquids as tar and molasses, it is evident that the force of cohesion is considerable. In such mobile liquids as water and alcohol, the cohesion is much less, although still measurable. While in liquids the force of attraction between molecules exceeds the effect due to molecular velocities, yet the difference is so small that liquid molecules readily slide over one another; thus the liquid takes the shape of the container.

In gases cohesion is so feeble and molecular motion so marked that the molecules of gases actually appear to repel one another. The force of cohesion is so small that gases expand indefinitely.

It seems apparent that the state of matter depends upon the balance between molecular forces and molecular velocities. Increasing molecular velocity by an increase of temperature converts a solid into a liquid and finally into a gas, and vice versa.

**86. Elasticity.** Such special properties of matter as tenacity, ductility, malleability, and hardness depend upon the cohesion of molecules. The elasticity of solids is also dependent upon this same force.

An object is said to be *elastic*, if it tends to resume its original form after the removal of any distorting force. The stretching of a rubber band illustrates the elasticity of *extension* or *traction*. The squeezing of a tennis ball exemplifies elasticity of *compression*. The twisting of a coiled spring is an example of the elasticity of *torsion*. The elasticity of *flexion* is exemplified by the bending of a strip of steel. In all these cases the object tends to resume its original form and volume when the stress is removed.

**87. Measurement of Elasticity.** Usually when one speaks of an elastic object, he means one that is easily distorted, such as rubber. In physics we use the term " elasticity " in a very different sense.

A substance is said to be highly elastic, or to have a high *elastic constant*, when it requires a great force to cause its deformation. If it requires twice as much force to stretch a wire of one kind a certain distance as to stretch a wire of the same cross-sectional area, but of different material, the same distance, the first material is said to have an elastic constant twice as great as the second. In this sense steel is highly elastic; in fact it is the most elastic substance known. Rubber has a very low elastic constant.

Rubber, however, has a fairly wide *limit of nearly perfect elasticity.* It may be distorted very much before its *elastic limit* is reached. When a substance is stretched beyond its elastic limit, it does not resume its original form after the distorting force is removed. Steel has a low elastic limit. A very great force is required to stretch a steel wire, but it cannot be stretched very far without becoming permanently distorted.

Liquids are perfectly elastic and they have a high elastic constant. Gases have a low elastic constant, but they are perfectly elastic. Elasticity of compression *only* applies to liquids and gases. Within the limits of perfect elasticity, the elastic constant of any substance equals $\frac{\text{stress}}{\text{strain}}$. *Stress is the acting force and strain the change produced.*

**88. Rebound.** If we throw an elastic object against a hard surface, it rebounds. Fig. 78 shows the angle of rebound and the angle of incidence. The angle *AOC* is the *angle of incidence*, or the angle that the line along which the object was thrown, makes with the perpendicular to the surface at the point of impact. The angle *BOC* is the *angle of reflection*, or the angle that the line of rebound makes with the perpendicular. The two angles are equal, if the object is perfectly elastic. There is one exception to this statement. A ball spinning on its axis as it moves does not rebound as shown in Fig. 78. When an object that is not perfectly elastic, a dead tennis ball, for example, is thrown against a hard surface, the angle of reflection, *ROC*, is greater than the angle of incidence. Uneven surfaces and balls that have lost some of their elasticity are responsible for many errors in baseball and tennis. A tennis ball that is "cut" to make it rotate is harder to handle.

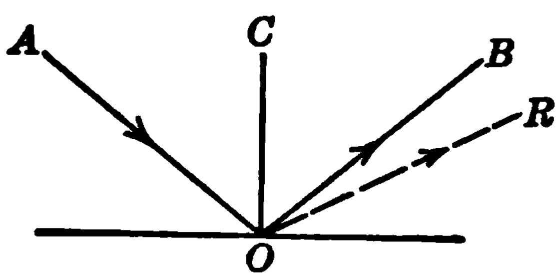


FIG. 78.— Angle of rebound.

**89. Hooke's Law.** If we fasten one end of a wire to a beam, as in Fig. 79, and add weights to the hanger attached to the other end, the wire will be gradually stretched as weights are added one by one. Suppose we find that a weight of 100 gm. stretches the wire 1 mm., then 200 gm. will stretch the wire 2 mm., 300 gm., 3 mm., and so on, until the elastic limit is reached. By such methods Hooke found that distortion is proportional to the distorting force, or, in general, *distortions of elastic material are directly proportional to the distorting force, provided the elastic limit be not exceeded.* The ordinary spring balance is a practical application of this law, since the 1 oz. divisions are equidistant.

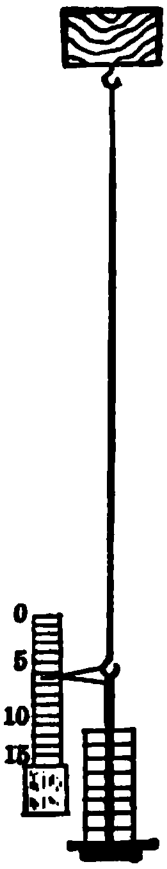



FIG. 79. — Tensile strength of wires.

**90. Strength of Materials.** It is very important for builders to know the coefficient of elasticity of structural materials. It is just as essential for engineers to know the breaking strength of the materials they use. In physical testing laboratories strong machines are used to measure the strength of materials. Such machines test the tensile strength of cables, ropes, wires, belts, etc. Tests are made of the compression strength of materials used for piers, pillars, posts, and foundations, which must not be crushed by the load they sustain. The propeller shaft of a steamship and the power shaft of an automobile must transmit power without the twisting of the shafts themselves. Torsion machines determine the resistance such shafts offer to a twisting stress. Beams and girders must not bend beyond the limit of perfect elasticity under the load they carry.

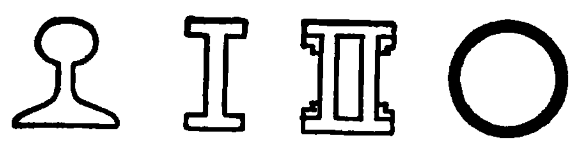


FIG. 80. — T-rail and beams in cross-section.

Several types of beams have been designed to give very great strength without undue increase in weight. Fig. 80

shows some of the types that are very much used by structural engineers.

When designing machines or structures of any kind, engineers always plan to use materials heavy enough to carry several times the load that is likely to be put upon them. This gives a *factor of safety*, for it provides for flaws in the material and for temporary overloading. A bridge which is made of material heavy enough to carry 50 tons is said to have a safety factor of 5, if its load is limited to a capacity of only 10 tons.

**91. Molecular Forces in Liquids.** It may be easily shown that the molecules of liquids have an attractive force for each other. It requires more force to pull a glass plate, in contact with a water surface, away from the water than it does to lift the plate. Since the plate is wet when pulled away, the extra force must have been needed to tear the water molecules apart. The adhesion of the water molecules to the glass is greater than their cohesion, hence water wets glass. If mercury had been used, the glass would not be wet by the mercury, since the cohesion of mercury molecules is greater than their adhesion to glass. The force of cohesion varies with different liquids, being fairly strong in some viscous liquids.

**92. Shape Assumed by a Free Liquid.** Since the molecules of liquids slide over one another readily, the force of gravity causes the surface of liquids to become level. If the force of gravity can be nullified, a small portion of *free* liquid will then assume a spherical form. The density of lubricating oils is less than that of water, but somewhat more than that of alcohol. Suppose we lower a drop of oil into a vessel containing a layer of alcohol floating on a layer of water. The oil floats in the liquid mixture and its shape is spherical. See Fig. 81.

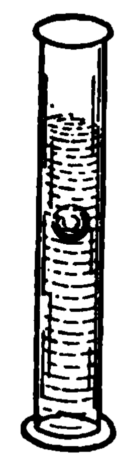


FIG. 81. — Free liquid assumes spherical shape.

The cohesive force pulls the molecules together until they have the smallest possible surface for their volume. Since a sphere has a smaller surface area per unit volume than any other geometrical figure, a free liquid assumes a spherical shape. Raindrops are spherical for the same reason. Mercury spilled on a table breaks up into small drops, since the effect of gravity on such small particles is small compared to the cohesive force of the molecules. Larger globules of mercury are distinctly flattened.

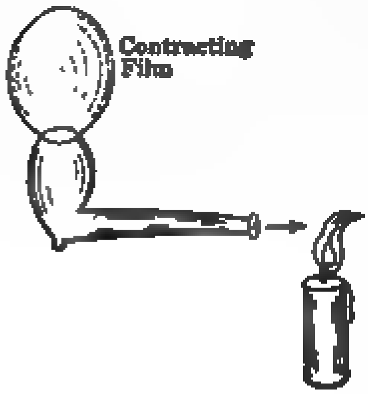


FIG. 82.— Film contracts and expels the air.

**93. Surface Tension and Liquid Films.** If we blow a soap bubble and then remove the pipe from the mouth, the bubble slowly contracts, forcing air out of the pipe-stem, Fig. 82. When we dip a wire ring containing a loop of thread, Fig. 83*a*, into a dish of soap-suds, a film is formed across the ring. If we break the film inside the loop with a hot wire, the unbroken film outside the loop contracts and pulls the thread into the form of a circle, Fig. 83*b*. These experiments show that *liquids behave as if a thin elastic film were stretched over their surfaces*. Since this film contracts to make the surface as small as possible, the force of contraction is often called the *surface tension of liquids*.

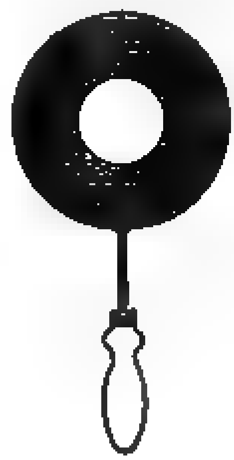


FIG. 83. — *a*. Soap film *b*. Soap film is contractile.

A very small needle will float, if laid carefully upon the surface of water, although its density is many times that of water. A careful examination of the water surface shows

that the needle floats in a little hollow, as shown in Fig. 84. The weight of the needle is not great enough to break the liquid film, or surface tension, of the water. A wet needle cannot be floated in this manner, hence this experiment is more easily performed if the needle is first covered with a film of oil. Small insects run over the surface of water, their weight being insufficient to break the surface tension. The surface tension of alcohol is less than that of water. Many oils have a greater surface tension. Soap added to water greatly increases the strength of the liquid film.

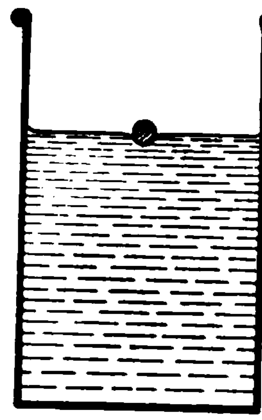


FIG. 84. — Needle floats on water.

Reference to Fig. 85 aids in the explanation of surface tension. A molecule at *A* is attracted equally in all directions by the cohesion of the surrounding molecules. A molecule at *B* is attracted laterally and downward, but not in an upward direction. Thus there is exerted upon the surface molecules an unbalanced force tending to pull them toward the interior of the liquid. This unbalanced, contractile force causes the surface to act like an elastic membrane.

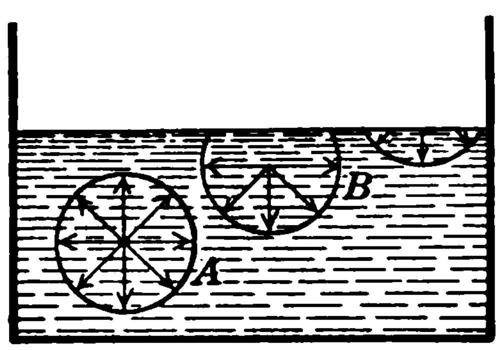



FIG. 85. — Molecule at surface is under uneven tension.

**94. Adhesion vs. Cohesion.** If the adhesion between the molecules of a liquid and the walls of its container is greater than the cohesion between its molecules, it wets the container and the edge of the liquid is slightly lifted. Thus the surface of such a liquid becomes *slightly concave.* See Fig. 86*a*. On the other hand, when the force of cohesion between liquid molecules exceeds their adhesion to the walls of the container, the liquid does not wet the vessel and the edges of its surface are slightly depressed. The surface of such liquids is *slightly convex.* Mercury in a glass vessel

A B

Fig. 86.— *a*. Liquids that wet vessel have concave surface. *b*. Liquids that do not wet vessel have convex surface.

is an example. See Fig. 86*b*. The crescent-shaped surface of a liquid column is called the *meniscus*.

**95. Capillarity.** In § 29 the statement was made that liquids in communicating vessels seek the same level. The statement is not rigorously exact, and a correction must be made for communicating tubes of small diameter. Experiment shows that water does not stand at the same level in communicating tubes of varying diameters, but rises higher in tubes of small diameter, Fig. 87*a*. When mercury is used, the depression is greater in tubes of small diameter, Fig. 87*b*. This elevation, or depression, of liquids in *capillary* (hair-like) tubes is known as *capillarity*.

A B

Fig. 87. — *a*. Capillarity of water. *b*. Capillarity of mercury.

Capillarity really depends upon adhesion and surface tension. The adhesion of water for the glass causes the surface of the water to become concave. Surface tension tends to decrease the surface area, or to flatten it by contraction. The two forces working together lift the liquid above the surrounding level. The height to which the liquid will be lifted depends upon its weight and the strength of the liquid film. In liquids like mercury cohesion makes the surface convex, and surface tension, by tending to flatten it, produces depression of the liquid in the tube.

**96. Laws of Capillarity.** Several laws that apply to capillarity have been verified by experiment: (1) *Liquids*

*rise in capillary tubes if they wet them; liquids that do not wet the tubes are depressed.* (2) *The elevation, or depression, is inversely proportional to the diameter of the tubes.* (3) *The amount of elevation or depression decreases as the temperature increases.*

**97. Capillary Phenomena in Everyday Life.** When one corner of a towel is held in water, other portions of the towel soon become wet. The spaces between the fibers are really small capillaries in which the liquid rises. The use of a towel in drying the hands is an application of capillarity. The absorption of ink by blotting paper, and the rise of oil in a lampwick, are further examples.

Capillarity may play an important part in the conservation of moisture in the soil. Rain-water disappears in several ways: (1) Part of it runs off directly; (2) part evaporates; (3) some trickles through the soil and becomes a part of the subterranean drainage system; (4) some of it is absorbed or held by the soil, to be used by the roots of plants. The amount thus retained depends upon the kind of soil and upon the size of its pores. In very compact soil the pores are small and capillary action brings the water to the surface, where it is lost by evaporation. Stirring the surface soil makes the pores larger and prevents a considerable portion of this loss. The so-called *dry farming* depends upon this principle. In Kansas, Nebraska, and other states where the rainfall is not much more than 15 to 20 inches annually, good crops may be grown by making the subsoil compact to prevent subterranean loss, and keeping the surface stirred to prevent loss by capillarity.

**98. Solution.** Every one knows that a lump of sugar or a piece of salt put into a glass of water dissolves, or goes into solution. In these cases the water is the *solvent;* the sugar or the salt, the *solute.* It is believed that a substance dissolves if the force of adhesion between its molecules and those of the solvent is greater than the cohesive force

binding together its molecules. The molecules of the solute occupy the spaces between the molecules of the solvent. It is probable that molecular motion also plays an important part in the advancement of these molecules through the pores of the solvent.

Several interesting facts concerning solutions should be noted: (1) *A solution is of the same nature throughout;* each unit volume of the solvent contains the same amount of solute. (2) *The solute does not separate from the solvent upon standing*, unless some of the solvent is lost by evaporation. (3) *Only a definite amount of solute can be dissolved in a given amount of solvent at a certain temperature.* If the solvent holds all the solute it can at that temperature, it is said to be *saturated.* (4) *The solubility of a solid generally increases with a rise of temperature.* (5) *The solubility of a solid varies with the nature of the solid and with the solvent used.* For example, rosin and shellac dissolve readily in alcohol, but they are scarcely soluble in water. Grease is quite insoluble in water, but it dissolves readily in gasoline. On the other hand, many substances dissolve in water that are quite insoluble in either alcohol or gasoline.

**99. Crystallization.** When the saturated solution of a solid is cooled or evaporated, some of the solid separates from the solvent in the form of crystals. Crystallization may also occur when a substance changes from the liquid to the solid state. During crystallization the molecules of the solid arrange themselves in regular geometric figures. The shape of the crystal depends upon the nature of the solid and the conditions under which crystallization occurs, Fig. 88. Granulated sugar, rock candy, and snowflakes are familiar examples of this beautiful phenomenon. The diamond differs from the graphite in your " lead " pencil only in the form in which the carbon particles of which it is composed have crystallized.

Fig. 88. — Plate of crystals. *A*. Rubellite. *B*. Quartz crystal in matrix. *C*. Galenite, or galena. *D*. Quartz crystals. *E*. Garnets on rock. *F*. Gypsum.

**100. Absorption of Gases by Solids.** Some porous solids, like charcoal, meerschaum, etc., have a great capacity for absorbing gases. Freshly heated charcoal absorbs 90 times its own volume of ammonia gas; it will absorb 35 times its volume of carbon dioxide. The absorption of gases by solids appears to be due to a condensation of the gas upon the surfaces of the solid; hence porous solids, having large surface areas, naturally have a great capacity for absorption. Tailors put fuller's earth on a grease spot and then add gasoline. The gasoline dissolves the grease which is absorbed by the fuller's earth. Charcoal is a good deodorizing agent, since it readily absorbs the gases that give rise to the odors. It was used very extensively in the World War for filling gas masks. It is very efficient in absorbing poison gases, especially when impregnated with certain chemicals. Every one in the United States collected cocoanut shells, pits, nuts, etc., to be used for making charcoal for gas masks. It was learned that charcoal made from these substances is about nine times as absorptive as that made from ordinary soft woods. See Fig. 89. The gases that are given off by such foods as fish and onions are readily absorbed by butter. For this reason butter kept in a refrigerator with onions soon acquires an "onion taste."

**101. Absorption of Gases by Liquids.** Milk absorbs gases given off by foods quite as readily as does butter. If we heat a little water in a test tube, bubbles of gas soon begin to rise through the water. This gas may be shown to consist of air which was absorbed by the water. Water absorbs carbon dioxide even more readily than it does air, while ammonia gas is so readily absorbed that it is possible to dissolve more than 1200 quarts of ammonia gas (S.T.P.) in one quart of ice water.

Heating a liquid decreases its capacity for absorbing gases. For this reason ammonia gas is liberated when we heat household ammonia.

FIG. 89. — Official gas mask. Within a week after the Germans released chlorine gas against the Canadians at Ypres, 2,000,000 simple gas masks were distributed to the French and British soldiers. Then projectiles filled with more dangerous gases were used. The simple masks made from veiling filled with "hypo" crystals were replaced by more efficient masks in which charcoal impregnated with chemicals is used to absorb or destroy the poison gases. (*U. S. Officials*)

An increase of pressure increases the capacity of liquids for absorbing gases. In charging soda fountains or in bottling carbonated beverages, carbon dioxide is forced into the liquid under a pressure of several atmospheres. When the pressure is released, part of the absorbed gas bubbles off and escapes at the surface of the liquid.

## SUMMARY

All matter is made up of very small particles called molecules; these molecules are in constant motion.

Gases expand indefinitely; they exert pressure; they diffuse readily, even through membranes; these facts show that the molecules of gases are in rapid motion.

The diffusion, evaporation, and osmosis of liquids are all evidences that their molecules are in motion. The diffusion and evaporation of solids furnish evidence of molecular motion.

Cohesion is the force of attraction between like molecules; adhesion is the force of attraction between unlike molecules.

Hooke found that elastic deformations are directly proportional to the distorting force, within the limits of perfect elasticity.

Liquids behave as if a thin elastic film were stretched over their surfaces. This film causes free liquids to assume a spherical shape.

Liquids that wet the tube are elevated by capillary action; those that do not wet the tube are depressed; the amount in either case is inversely proportional to the diameter of the tube.

The solubility of solids increases as the temperature increases. The solubility of gases decreases with an increase in temperature. An increase in pressure increases the solubility of gases in liquids.

## QUESTIONS AND PROBLEMS

1. Why is osmosis so very important?

2. Why does not the carbon dioxide of the air collect near the floor of a room?

3. Why does putting salt on a garden snail or slug cause it to become wrinkled?

4. Explain the action of a towel in drying the hands.

5. Why is paper that is to be used with ink covered with sizing?

6. When a glass rod is cut off its edges are very sharp. Why do they become rounded when they are held in a flame until the glass is softened?

7. Shot are made by pouring molten lead on sieves supported at a considerable height, from which drops of molten lead fall into a vessel of water. Why are they rounded?

**8.** Chemists hold a glass rod against the side of a beaker from which a liquid is being poured. What is its function?

**9.** Is the air inside a soap bubble denser or rarer than the air outside?

**10.** Fish die in an aquarium unless the water is frequently renewed. Explain.

**11.** Why does effervescence occur when soda water is drawn from a soda fountain?

**12.** If the 10-gm. divisions on a spring balance are 2 mm. apart, how far will the spring be stretched by a load of 250 gm.?

**13.** A wire 1 mm. in diameter is stretched .1 mm. by a certain weight. How far will a wire 2 mm. in diameter be stretched by the same weight, if it is of the same material and of equal length?

*Suggested Topics.* Dry Farming. How Moisture Is Secured to Supply the Spring Wheat of Minnesota. Activated Charcoal and the World War. The Ultramicroscope.

# CHAPTER 5

## FORCE

**102. Force** has already been defined as a "push" or a "pull"; it is sometimes defined as muscular exertion or its equivalent. Force may act in any direction; sometimes

FIG. 90. — One of the small tanks used during the World War. The caterpillar tractor enables the tank to travel over soft or uneven ground. These "whippet tanks" carried machine guns. They could travel as fast as infantry. The larger tanks, Fig. 337, exerted force enough to plow through barbed wire entanglements, uproot small trees, or overthrow small buildings.

it results in moving an object, or it may merely tend to move it. On the other hand, force may stop a moving

**Sir Isaac Newton** (1642-1727) was a famous English philosopher. He stated the law of gravitation and the laws of motion. He discovered the composition of white light, and explained the color fringe of films. In his explanation of the reflection, refraction, and diffraction of light he used as a basis the corpuscular theory. In mathematics he laid the foundation for the calculus.

**Galilei Galileo** (1564-1642) was an Italian physicist. At the age of eighteen he observed that the oscillations of a swinging chandelier were regular, and invented the pendulum as a time-keeper. From the leaning tower at Pisa he dropped objects of different density and noticed that all struck the earth at practically the same time. Galileo invented the refracting telescope and the thermometer. He showed that the path of a projectile is a parabola.

body or it may only tend to stop it. Fig. 90 shows one of the "tanks" or land battleships that played so important a part in the battles during the World War. The large ones exerted great force, breaking down barbed wire entanglements and uprooting trees.

**103. Force of Gravitation.** Probably the most familiar force in nature is that known as *gravitation*. Every one knows that the earth exerts an attractive force that tends to pull all objects toward it. We say objects fall to the earth because they are attracted by gravity. Sir Isaac Newton found that gravitation is *universal*, and that objects have a *mutual* attraction. Not only does the earth attract objects, but it is mutually attracted by these objects. The force of attraction decreases as the square of the distance between their centers increases. Newton first announced the law of universal gravitation: *Every body in the universe attracts every other body with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.* Hence the earth attracts three bricks with three times as much force as it attracts one brick. If the mass of the earth were doubled, it would attract one brick with twice as much force as it does at present. An object on the surface of the earth is about 4000 miles from its center. If an object were taken to a height of 1000 miles, or 5000 miles from the earth's center, the attraction of the earth for it would be only $(4000)^2/(5000)^2$ as great.

**104. Weight.** *The weight of a body is really a measure of the earth's attraction for that body.* When we say that a man weighs 200 lb., we mean that the measure of the earth's attraction for that man is 200 lb., or that the earth pulls that man toward itself with a force of 200 lb. Since all parts of the earth's surface are not equidistant from its center, we would expect the weight of an object to vary in different localities. An object at the top of a high moun-

tain weighs slightly less than it does at the base. Since the earth is a flattened sphere, the poles are nearer the center than the equator; for that reason objects weigh slightly more at the poles than they do at the equator.

The mass of the sun is so much greater than that of the earth that an object which weighs 100 lb. here would weigh about 2700 lb. at the surface of the sun. On the moon, however, the force of gravity is so much smaller that we would weigh only about $\frac{1}{6}$ as much as we do on the earth. An athlete on the moon could easily jump 30 or more feet high; on the sun he would be unable to lift his foot.

**105. Units of Force.** To measure forces, or to compare them, some definite units must be defined. The units of force commonly used in physics are the *gravitational* units: the *gram of force* and the *pound of force.* A gram of force is the pull which the earth exerts upon one gram of mass. *A gram of force acting continuously on one gram of mass for one second imparts to it a velocity of approximately 980 cm. per second. A pound of force acting for one second upon a mass of one pound imparts to it a velocity of 32.16 ft. per second.* For the same reason that weight varies, these units of force also vary. The values given above are the approximate values for the latitude of New York.

FIG. 91. — Spring balance.

The *dyne* and the *poundal* are *absolute* units of force; they are of value in defining other units of measurement, since they are independent of the varying force of gravity. *One dyne acting for one second upon a gram of mass imparts to it a velocity of one cm. per second.* The dyne is approximately $\frac{1}{980}$ of the gram of force; or, 980 dynes equal 1 gram of force. *One poundal acting for one second upon one pound*

*of mass imparts to it a velocity of one foot per second.* One pound of force equals 32.16 poundals.

**106. How Force Is Measured.** The spring balance is an application of Hooke's law. We may use it to measure the magnitude of forces. The pull of the earth for one gram of mass suspended from the hook of a balance will stretch the spring a certain distance. The pull upon a two-gram mass will stretch the spring twice as far, and so on. The graduations are marked upon the face of the balance, which is independent of the spring. A pointer attached to the spring indicates the reading. See Fig. 91.

**107. Representation of Forces.** To describe a force we must designate the *point at which it is applied*, the *direction in which it acts*, and *its magnitude*. These three factors must also be considered if we wish to represent a force graphically. Suppose we wish to represent a force of 10 gm. acting in an easterly direction upon the point $P$. We may use a straight line ten units long drawn in an easterly direction from the point $P$ to represent this force, Fig. 92. Any convenient unit of length may be used, but the same unit must be used in each case if several forces are to be represented. Fig. 93 represents two forces, one of 15 gm. acting in a westerly direction upon the point $P$; the other, a force of 20 gm. acting in a southerly direction upon the same point.

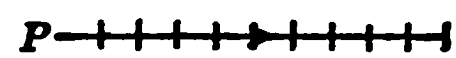



FIG. 92. — Graphic representation of a force.

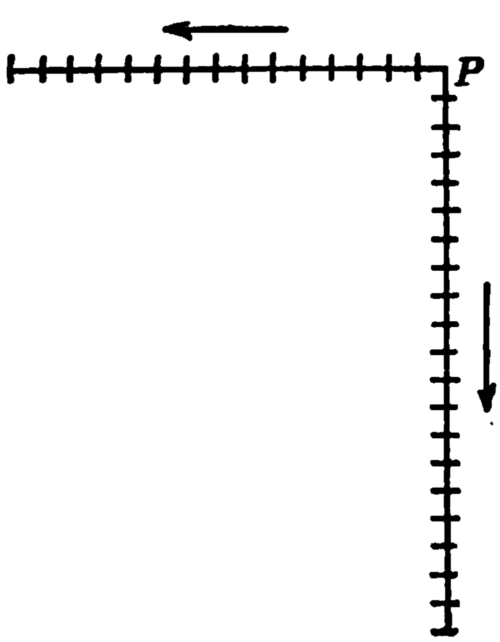



FIG. 93. — Forces acting at an angle.

**108. Resultant.** Two or more forces often act simultaneously upon the same object. If desired, it is possible to find the point of application, the direction, and the magnitude of a *single* force that could produce the same effect as all the forces acting con-

jointly. *A single force that could produce the same effect as two or more forces acting together is called the resultant of those forces. If the resultant were substituted for the forces, it would produce the same effect.*

When two forces act in the same direction in a straight line, the resultant is equal to the sum of the forces; when two forces act in opposite directions in the same straight line, the resultant equals the difference between the forces.

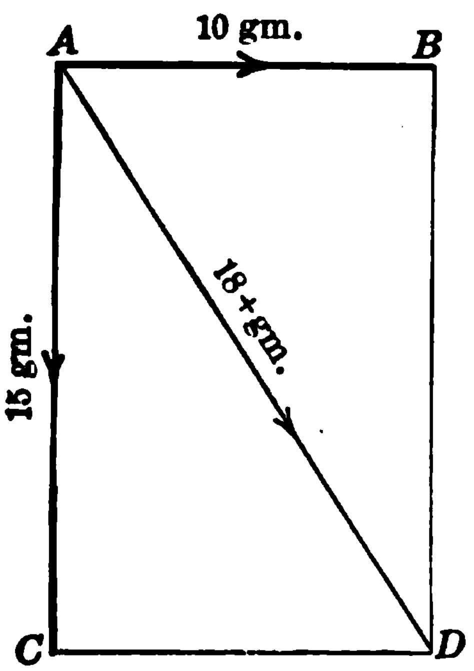


FIG. 94. — Parallelogram of forces.

**109. Resultant of Forces Acting at an Angle.** Suppose a force of 10 gm. acts in an easterly direction upon an object at point $A$, and a force of 15 gm. acts in a southerly direction upon the same point. From a consideration of Fig. 94, it is obvious that the first force acting alone would move the object along the line $AB$ to $B$; the second force acting alone would move it along $AC$ to $C$. If the two forces acted *successively* upon the object, it would arrive at point $D$; if they acted *simultaneously*, it would also arrive at $D$, but its line of motion would be along the diagonal of the parallelogram of which the two forces are sides. *The resultant of two forces acting at an angle upon a given point is equal to the diagonal of a parallelogram of which the two forces are sides.* If the two forces act at right angles, the magnitude of the resultant may be computed by extracting the square root of the sum of the squares of the two sides. In the above example,

$$\sqrt{(10)^2+(15)^2}=18^{+}\text{ gm.}$$

If the two forces do not act at right angles, the approximate value of the resultant may be found by drawing the parallelogram to scale and then carefully measuring the diagonal.

If three forces act at different angles upon a point, the resultant may be found by first finding the resultant of any two forces, and then completing a second parallelogram by using as sides the diagonal of the first parallelogram and the third force. The diagonal of the second parallelogram is the resultant of the three forces acting conjointly. In a similar way the resultant of any number of forces can be found.

**110. Equilibrant.** Sometimes it is desirable to find the magnitude, point of application, and direction of a force which could be applied to produce equilibrium, or to prevent motion. From the preceding section we learned that a force of $18^+$ gm. would produce the same effect as the two forces, $AB$ and $AC$, Fig. 94. A force which would just counteract the force of $18^+$ gm., represented by $AD$, Fig. 95, must be just equal in magnitude and opposite in direction. Hence a force of $18^+$ gm. acting along the line $AE$, will just produce equilibrium with the forces $AB$ and $AC$. Such a force is called the equilibrant. *The equilibrant of two or more forces is always equal and opposite to their resultant.*

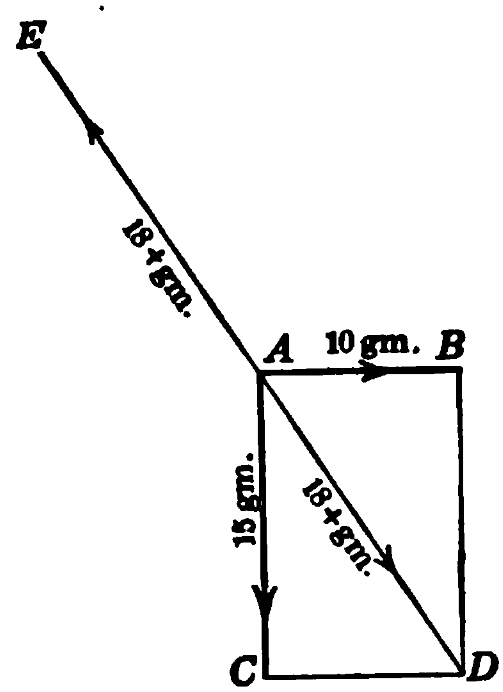



FIG. 95. — Equilibrant prevents motion.

**111. Moment of a Force.** Suppose we have two forces acting upon a bar $AB$, which is fastened to a pivot at $C$, Fig. 96. The tendency of the force $F$ to produce rotation about the center of moments $C$, or the axis of rotation, depends not only upon the magnitude of the force itself, but also on the length of the arm upon which it acts. *The*

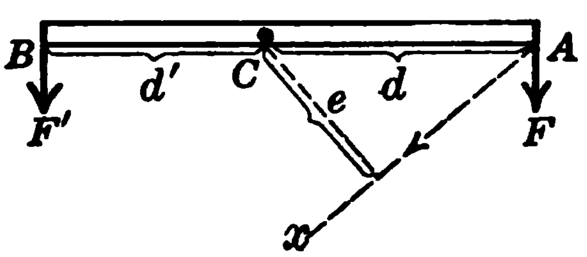



FIG. 96. — Moment of a force.

*effectiveness of a force in producing rotation is called the moment of the force. The value of the moment of a force is equal to the product of the force times the length of the arm upon which it acts.* Let the distance $AC = d$, and the distance $BC = d'$. The tendency of the force $F$ to produce rotation in a clockwise direction, or its moment about $C$, is equal to the product $Fd$. The counterclockwise moment of the force $F'$ about $C$ is equal to the product $F'd'$.

If the forces are not applied perpendicularly to $AB$, then the distance $d$ is not the length of the arm $AC$, but it is the perpendicular distance from $C$ to the line of direction of the force. For example, the moment of the force $X$ about $C$ equals $Xe$, and not $Xd$.

**112. Parallel Forces.** Two horses pulling a loaded wagon furnish an example of parallel forces. The load on a bridge is distributed between the abutments supporting the bridge. Two boys lifting a weight placed on a stick between them furnish a third example of parallel forces. *The resultant of two parallel forces acting in the same direction is equal to the sum of the two forces. The resultant must be applied at the center of moments.*

**113. Resolution of Forces.** We have just learned how to find a single force that could produce the same effect as two component forces. Sometimes it is necessary to work the principle of composition of forces backward; it is possible if we know one component, the resultant, and the included angle, to find the other force which was unknown. To do so, we must construct a parallelogram, using the resultant as the diagonal and the known force as one side. The other side of the parallelogram represents the other force. Since the angle between the diagonal and one side is known, it is a simple matter to construct the parallelogram.

PROBLEM. Two forces act upon the point $A$; one force of 8 gm. acts in a southerly direction; an unknown force acting with the 8-gm. force produces the same effect as a single force of 10 gm. acting in a

direction 37° East of South. Find the magnitude and direction of the unknown force.

*Solution.* Construct a parallelogram, using for one side the 8-gm. force, direction southerly. Using a protractor, measure off an angle of 37°, and draw a line to represent the resultant, 10 gm. This resultant is the diagonal of the parallelogram. Complete the parallelogram. The other side represents the unknown force.

It often happens that a force acts upon an object in a direction in which it is not free to move. A switch engine may move a car on an adjacent track by means of a pole held at an angle between the engine and the car. An object resting upon an inclined plane is acted upon by gravity with a force equal to its weight. See Fig. 97. Since it cannot move in this direction, the force $OW$ is resolved into two components; one of them, $OD$, acts at right angles to the plane tending to break it; the other force, $OR$, acts parallel to the plane, tending to pull the object down the plane. The triangles $ABC$ and $WOR$ are similar. Hence $OR : OW = BC : AB$. Since $OW$ is proportional to the weight of the object, $AB$ equals the length of the plane, and $BC$ the height of the plane, the force $OR$ tending to pull the object down the plane bears the same relation to the weight of the object that the height of the plane does to its length.

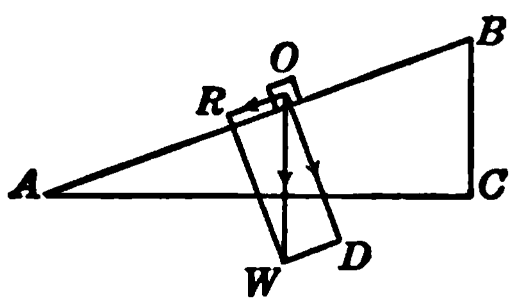



FIG. 97. — Resolution of a force into its components.

$$\text{Therefore, } F : W = h : l.$$

In the same manner it may be shown that the force tending to break the plane bears the same ratio to the weight that the base of the plane does to its length.

**114. How an Airplane Is Supported.** Airplanes are heavier than air, hence they must be partially supported by the upward component of some force. In the monoplane type there is one huge plane tilted so that the front edge

stands slightly higher than the rear edge. The biplane type has two such planes. Powerful gasoline engines turn a large propeller, which drives the airplane forward. In Fig. 98, let *AB* represent a plane which is being driven forward in the direction *CP*. As the plane is driven forward it produces a breeze which makes the conditions the same as if a strong wind were blowing in the direction of the arrows and the plane standing still. This wind force is resolved into two components, one acting vertically, represented by *CF*; the other component, *CD*, opposes the action of the propeller.

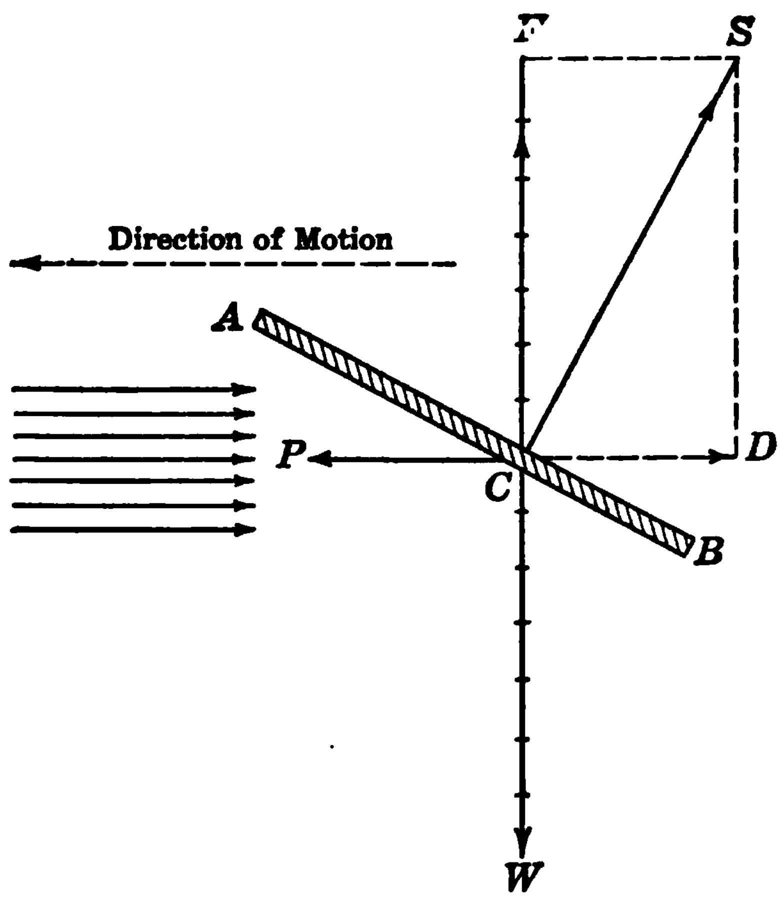


FIG. 98. — Wind force is resolved into two components.

Unless the component *CF*, which forces the plane upward, equals *CW*, which represents the weight of the plane and its load, the plane will fall. To keep the plane moving forward, the force of the propeller, *CP*, must exceed the component *CD*. Fig. 99 shows Orville Wright making the first flight in a power-driven plane. Figs. 100 and 101 show the front and rear view of a modern type of "heavier-than-air" machine.

**115. Center of Gravity.** Since the earth attracts every particle of an object, evidently the resultant of all these parallel forces is the sum of all of them, and it is equal to the weight of the object. The point of application of this resultant is called the *center of gravity*. The center of gravity of an object is the point at which all the weight appears to be concentrated. It is the point at which the object would balance upon the point of a knife.

Fig. 99. — First flight with a power-driven aeroplane at Kitty Hawk, North Carolina, on the 17th of December, 1903. Orville Wright in the plane, and his brother, Wilbur, on the ground. Of four flights made that morning, the longest was 59 seconds, and the distance 852 ft.

Orville Wright. Wilbur Wright.

The Wright brothers are the inventors of the power-driven aeroplane.

Fig. 100. — Front view of a modern airplane.

Fig. 101. — Rear view of a modern airplane.

**116. Center of Gravity by Experiment.** The center of gravity of a body may be found experimentally by suspending it so it is free to turn about a point, first from one position, and then from at least two others. When we suspend a plumb line, the line along which it comes to rest will, if produced, pass through the center of gravity of the earth. Now let us suspend from the same point the object whose center of gravity is to be found. It swings about the point $P$, Fig. 102, finally coming to rest with its center of gravity at the lowest possible position, and at some point along the plumb line. After drawing this line on the object, let us suspend it from point $B$, and again draw a line in the direction indicated by the plumb line. Repeat the operation, suspending the object from point $C$. The three lines intersect at the center of gravity. In mechanics, it will often be very convenient to consider that all the weight of an object is concentrated at its center of gravity.

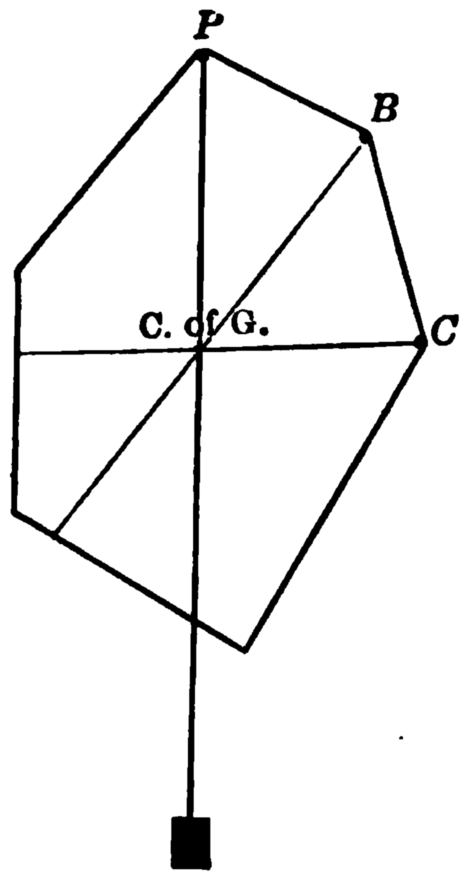



FIG. 102.— Finding center of gravity.

**117. Equilibrium.** *An object is said to be in equilibrium when the resultant of all the forces acting upon it is zero.* Any unbalanced force will swing it from its position of rest. To secure equilibrium, two kinds of motion must be prevented: translatory, or motion along a line; and rotary, or motion about a point acting as a pivot. Suppose we have two parallel forces, $D$ and $E$, of 80 and 120 lb. respectively, acting upon a bar at points $A$ and $B$, Fig. 103 *a*. A force of 200 lb. applied in the opposite direction at $O$ will prevent translatory motion, but it will not prevent rotary motion. Rotary motion may be prevented if the force of 200 lb. is applied

at the center of moments, $X$, Fig. 103 *b*. It must be applied nearer the greater force, at such a point that the lengths of the arms upon which the forces act will be inversely proportional to the magnitude of the forces.

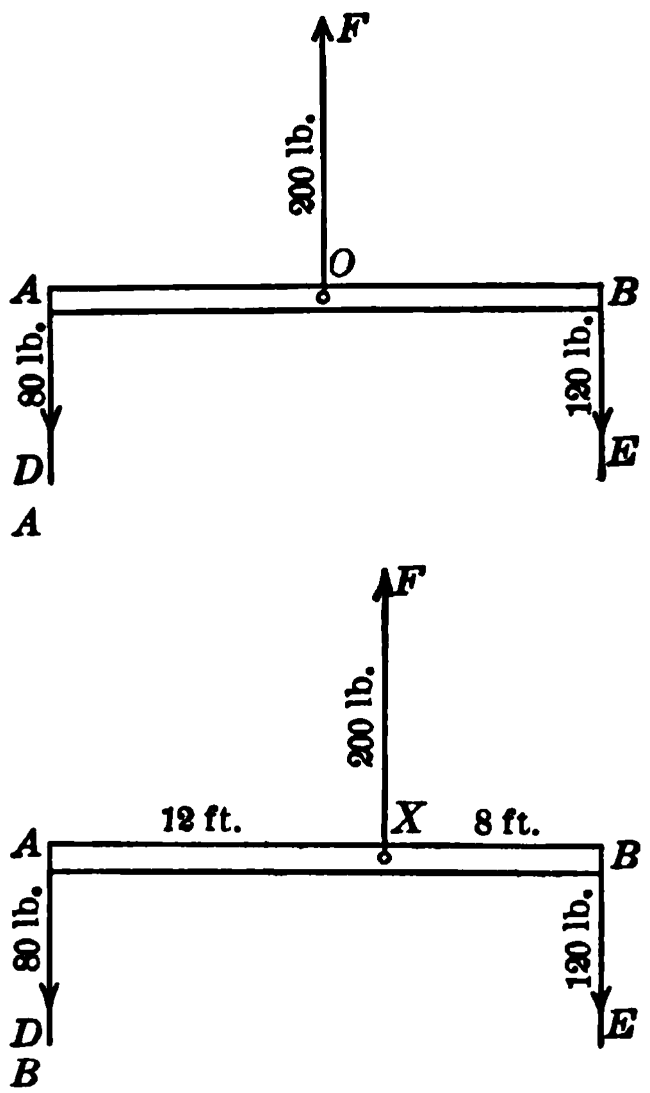



FIG. 103. — *A* Translatory motion prevented. *B* Rotary motion prevented.

If $AB$ is 20 ft. long, then one arm must be $\frac{80}{200}$ of 20 ft., or 8 ft.; the other arm will be $\frac{120}{200}$ of 20 ft., or 12 ft. If we make $AX$ 12 ft. long, the counterclockwise moment about $X$ equals $80 \times 12$, or 960. $BX$ will then be 8 ft. long, and the clockwise moment about $X$ equals $120 \times 8$, or 960. Therefore both translation and rotation are prevented, and the bar is in equilibrium. *Any number of parallel forces are in equilibrium if the sums of the opposite forces are equal and the sums of the clockwise and counterclockwise moments are equal.*

**118. Stable Equilibrium.** If an object is in stable equilibrium, it cannot be overturned without first raising its center of gravity. If slightly tipped, it tends to return to its former position. The blocks shown in Fig. 104 are both in stable equilibrium, but their degree of stability differs. To overturn block ($A$) about the edge $E$, the center

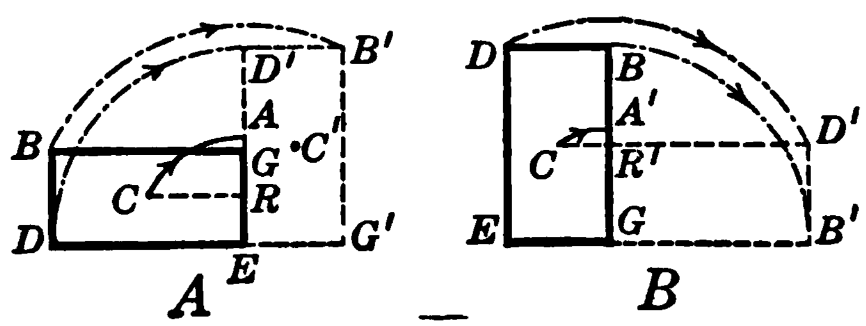



FIG. 104. — Stability increases with area of base.

of gravity $C$ must be raised to the point $A$. When the center of gravity passes beyond the vertical line $AE$, so that it falls outside the base, the block will be overturned and fall to the position shown by the dotted lines. The same block, standing on end as in Fig. 104 *b*, is also in stable equilibrium, but it is not so hard to overturn it as when it lies flat on its side. In position ($A$) the center of gravity must be lifted the vertical distance $RA$ before it can be overturned; in position ($B$) the center of gravity must be lifted from $R'$ to $A'$ before it can be overturned. $RA$ is much greater than $R'A'$, hence the greater stability when the block lies on its side. *The stability of an object may be increased by enlarging the base and by having the center of gravity as low as possible.*

The base of support is represented roughly by the area inclosed by the perimeter drawn around the supporting members. The dotted lines of Fig. 105 inclose the area of the base. With a three-legged stool the base is triangular; with an ordinary chair it is a rectangle.

FIG. 105. — Base of support.

A boat loaded with freight sinks very low in the water; at the same time the center of gravity is lowered, increasing its stability. A load of stone is less apt to be upset than a load of hay, since the center of gravity of a load of stone is lower.

**119. Unstable Equilibrium.** An egg standing on its end is in unstable equilibrium. A person walking a tightrope is another example. As soon as the slightest displacement occurs in either case, the center of gravity falls outside a plumb line perpendicular to the point of support; it begins to be lowered at once, and the object falls. In unstable equilibrium the center of gravity is above the point of support.

**120. Neutral Equilibrium.** A ball lying on a table is in neutral equilibrium. A cylinder or a cone lying on its side,

and a wheel free to turn upon its axle, are other examples of neutral equilibrium. Such objects come to rest in any position since the center of gravity is neither raised nor lowered when the object is overturned. See Fig. 106.

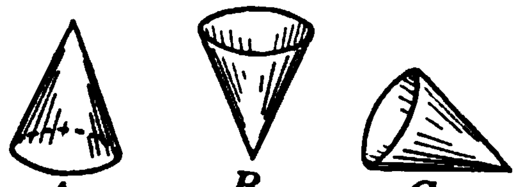


FIG. 106. — Types of equilibrium.

## SUMMARY

Force is a " push " or a " pull "; it tends to produce, change, or check motion.

Gravitation is the attraction between masses. The force of attraction between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

The gram of force and the pound of force are gravitational units of force. The dyne and the poundal are absolute units of force.

The resultant of two or more forces is that single force which could produce the same effect as two or more forces acting together. The resultant of forces acting in the same direction is their sum; the resultant of forces acting in opposite directions is their difference.

The resultant of two concurring forces acting at an angle is equal to the diagonal of the parallelogram of which the forces are adjacent sides. The equilibrant is that force which produces equilibrium; it is equal to the resultant and opposite in direction.

The center of gravity of a body is that point at which all its weight appears to be concentrated.

An object is in equilibrium when the resultant of all the forces acting upon it is zero. The stability of an object is increased by broadening its base and by lowering its center of gravity.

## QUESTIONS AND PROBLEMS

1. If a hole were bored through the earth and a ball dropped into it, where do you think it would come to rest? Explain.

2. When an apple falls to the ground, does the earth rise to meet it? Give a reason for your answer.

3. Would a gram of force at the sun be greater than a gram of force on the earth's surface? Would a dyne be greater on the sun's surface?

4. Why does the oil-can shown in Fig. 107 right itself when placed on its side?

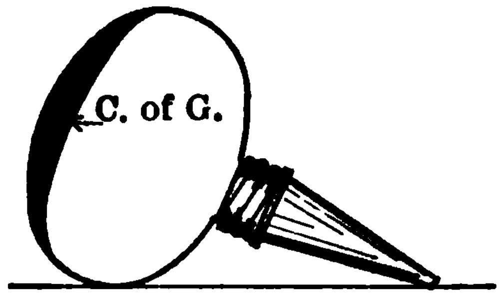


FIG. 107. — Oil-can.

5. Why does a man lean forward as he climbs a hill?

6. In what two ways can a football guard increase his stability?

7. Why would you lower the handle of a lawn mower in pushing it through tall grass? Use a diagram to aid your explanation.

8. Why does a ball roll down an inclined plane?

9. Which is more apt to "turn turtle," an "underslung" or an "overslung" automobile?

10. A force of 30 gm. acts in an easterly direction. Upon the same point a force of 25 gm. acts in a southerly direction. Represent graphically and find the magnitude of the resultant.

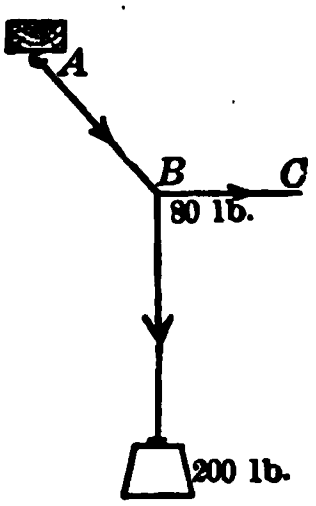


FIG. 108. — Component of force.

11. Find the resultant of two forces, one of 60 gm. acting easterly and the other of 45 gm. acting northerly.

12. A weight of 200 lb. is supported by a rope. If the rope is drawn aside along *BC*, Fig. 108, by a force of 80 lb., find the tension on the rope *AB*.

13. The resultant of two forces acting on an object is 20 lb. The forces are equal and act at right angles. Find their magnitude.

14. Two forces, 8 and 10 lb. respectively, act upon a point *P*. Find their resultant: (*a*) when the angle between them is 180°; (*b*) when the angle between them is 120°; (*c*) when the included angle is 90°; (*d*) when it is 60°; (*e*) when it is zero.

15. A load of 140 lb. is carried by two boys on a stick 3.5 ft. long. If the load is placed 2 ft. from the smaller boy, how many pounds does each boy carry?

16. A pair of double-trees is 32 in. long. If the hole is bored 15

in. from one end, what fractional part of the load does each horse pull, if hitched as shown in Fig. 109?

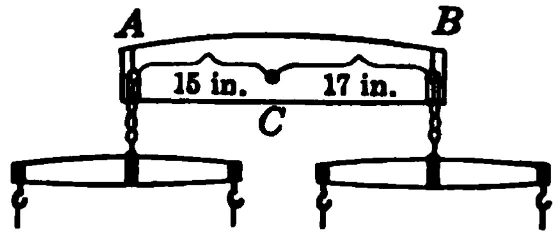


FIG. 109. — Double-trees, or evener (parallel forces).

**17.** A bridge is 200 ft. long. A load of 5 tons rests on the bridge at a point 30 ft. from one end. What load does each abutment sustain, in addition to the weight of the bridge?

**18.** A bridge 80 ft. long weighs 6 tons. An engine weighing 8 tons crosses the bridge. What is the maximum load sustained by each abutment? the minimum load? the load when the engine is 25 ft. from one end?

**19.** A bar 6 ft. long is pivoted at *C*, 30 in. from the end *A*. A downward force of 40 lb. is applied at *A*; at *B*, the other end, an upward force of 60 lb. is applied; at *D*, 10 in. from *A*, there is an upward force of 100 lb.; at *E*, 12 in. from *B*, there is a downward force of 120 lb. Where must a force of 94 lb. be applied to produce equilibrium, and what is its direction?

*Suggested Topics.* The Wright Brothers and the Airplane. Materials Used in Airplane Construction. Airplanes and the World War.

# CHAPTER 6

# MOTION

## A. TYPES OF MOTION

**121. Motion.** We may define motion as a change of place or position. Both motion and rest are relative terms. A person sitting in a railway coach is at rest with respect to the parts of the coach, but he may be in motion with respect to the surrounding landscape. One walking along the decks of a moving steamship is in motion with respect to the parts of the ship and also with respect to the earth's

Fig. 110. — Broadway Limited running 60 miles per hour. This train runs between New York and Chicago (about 950 miles) in 20 hours.

surface. Motion is *rectilinear*, if the object moves along a straight line; if the object moves along a curved line, the motion is *curvilinear*.

**122. Velocity** is the rate of motion; the velocity of an object is the distance it moves in a given unit of time. Velocity may be expressed in miles per hour, feet per second, kilometers per hour, etc. For example, we say that a train has a velocity of 60 mi. per hr. (Fig. 110), that a rifle

bullet travels with a velocity of 3000 ft. per sec., or that a man runs with a velocity of 30 ft. per sec. The word " speed " is practically synonymous with " velocity "; the slight difference in meaning is not of importance for secondary school pupils. Motion is *uniform* when the velocity is constant, or when the distance traversed is the same for each succeeding unit of time. A car that *maintains* a velocity of 30 miles per hr. is an illustration of uniform motion. When the distances traversed in equal periods are unequal, the motion is *variable*.

**123. Acceleration.** *The rate at which the velocity of a body changes is its acceleration.* If a body moves 1 ft. the first second, 3 ft. the next second, 5 ft. the third second, etc., we have an example of accelerated motion. Since the velocity increases 2 ft. per sec., the acceleration for one second is 2 ft. per sec. Since the acceleration is constant, the motion is *uniformly accelerated.* A body that moves 2 ft. the first second, 5 ft. the next second, and 10 ft. the third second furnishes an example of accelerated motion, but the acceleration is not uniform. An object that moves 7 ft., 5 ft., 3 ft., and 1 ft. in each of four successive seconds is an example of *uniformly retarded*, or *negatively accelerated* motion. In accelerated motion, where the velocity varies each second, *the velocity at the end of any second is equal to the distance the body would move during the next second, if at that instant it ceased to be accelerated.*

**124. Laws of Accelerated Motion.** Galileo made a large number of experiments with falling bodies. He dropped objects of different material from the top of the leaning tower at Pisa and found that they all reached the ground at nearly the same time. Even paper fell rapidly when rolled into a compact ball. He used an inclined plane also to study the laws of falling bodies. A ball rolls down an inclined plane with uniformly accelerated motion, but the distance traveled in any number of seconds is so much less than that of freely

falling bodies, that the distance can be more easily measured.

If we were to repeat his experiments by letting a ball roll down a grooved plane which is made just steep enough so the ball rolls 1 ft. the first second, we should obtain results about as follows:

Ball rolls 1 foot in 1 second;
4 feet in 2 seconds;
9 feet in 3 seconds;
16 feet in 4 seconds;
25 feet in 5 seconds.

Thus we see that the distance the ball rolls is directly proportional to the square of the number of seconds. It is also easy to deduce the following observations:

The ball rolled 1 foot the *first* second;
3 feet the *second* second; $(4-1)$
5 feet the *third* second; $(9-4)$
7 feet the *fourth* second; $(16-9)$
9 feet the *fifth* second. $(25-16)$

The figures 1, 3, 5, 7, and 9 show that the motion was *uniformly* accelerated; the acceleration $a$ is 2 feet per second for each second of time. Since velocity is the rate a body moves in a given time, and acceleration the change in rate for a given time, it is correct to use the term acceleration per second per second (rate of change of velocity per second), or acceleration per hour per hour. To avoid apparent repetition, the expression "acceleration per second" will be used in this text when both the velocity and acceleration are rated in seconds. When a body starts from rest and travels with uniformly accelerated motion, *the acceleration equals twice the distance traversed during the first second.*

The initial velocity was zero; the gain in velocity, or acceleration, was 2 ft. per sec.; therefore the velocity at the end of the fifth second was $5 \times 2$ ft. per sec. From these simple observations, it is possible to deduce laws that apply to all cases of uniformly accelerated motion.

LAW 1. *If the acceleration is uniform, the velocity at the end of any second is directly proportional to the time.*

Therefore, final velocity equals acceleration times the time.

Algebraically, $v = at.$ (Formula 1)

In all types of motion, the total space passed over, $S$, equals the *average* velocity times the number of seconds, $t$; or, *distance = average velocity × time.*

The average velocity for any given number of seconds equals one half the sum of the initial and final velocities, or average velocity $= \frac{\text{initial velocity} + \text{final velocity}}{2}$. For a body starting from rest the initial velocity is zero; the final velocity equals $at$; from these values the second law may be derived:

$$\text{average velocity} = \frac{\text{zero} + at}{2},$$

whence we get by substitution,

$$\text{distance} = \frac{at}{2} \times t, \text{ or } S = \tfrac{1}{2}at^2. \qquad \text{(Formula 2)}$$

LAW 2. *If the acceleration is constant, the distance traversed in any given number of seconds is equal to one half the acceleration times the square of the number of seconds.*

In solving problems, we may use formula (1) to find $v$, $a$, or $t$, if two of these quantities are known. If any two of the following, $a$, $t$, and $S$, are known, the third may be found by the use of formula (2). Given $a$, $v$, and $S$; any two of them known, and the third to be found. Solving formula (1) for $t$, and substituting in formula (2) the value thus obtained, we get $v = \sqrt{2aS}$. (Formula 3)

The formula, $s = \tfrac{1}{2}a(2t - 1)$, may be used to find the distance traversed in any *given* second, the *sixth* or *eighth*, for example.

**125. Retarded Motion.** These laws and formulas also apply to retarded motion. Suppose we desire to find how far a car, traveling 30 mi. per hr., or 44 ft. per sec., will run

before it can be stopped by the brakes, if they are capable of retarding the car 10 ft. per second. The problem is the same as if we asked how far a car must travel to attain a speed of 30 mi. per hr., if the acceleration is 10 ft. per second.

*Solution.* Velocity and acceleration are known; distance is to be found. These three quantities all occur in formula (3).

$$v = \sqrt{2aS}. \qquad \text{(Formula 3)}$$

$$44 = \sqrt{2 \times 10 \times S}, \text{ by substitution.}$$

$$20S = (44)^2, \text{ and } S \text{ equals } 96.8 \text{ ft.}$$

**126. Freely Falling Bodies.** If we make the plane used in repeating Galileo's experiments steeper, the acceleration increases. When the plane is vertical, the ball becomes a freely falling body. The acceleration is due to the continuous attractive force of gravity, but now it is not resolved into two components as before. See Fig. 97, § 113. The force of gravity pulls directly upon the ball.

We have learned that the "gram of force," which is a gravitational unit, imparts to 1 gm. of mass a velocity of 980 cm. per second in one second of time. Since $v = at$, then, from the above definition, $a$ is equal to 980 cm. per second at the latitude of New York. The laws of accelerated motion apply to freely falling bodies, but since the *acceleration due to gravity* is always the same at a given locality, the letter $g$ is used instead of $a$ to represent acceleration. For New York, $g = 980$ cm., or 32.16 ft. per second. The formulas derived in § 124 then become,

$$v = gt \ (1); \quad S = \tfrac{1}{2}gt^2 \ (2); \quad v = \sqrt{2gS} \ (3); \quad s = \tfrac{1}{2}g(2t-1) \ (4).$$

**127. Objects Fall at the Same Rate in a Vacuum.** When Galileo performed his celebrated experiments with falling bodies, he found that dense objects fell rather more rapidly than lighter objects. There was so little difference in the majority of cases that he concluded the unequal rate must be due to the resistance of the air, and *that all bodies would fall at the same rate in a vacuum.*

The invention of the air pump made it possible to prove the correctness of Galileo's theory. A long glass tube, containing a feather and a coin, is inverted. The feather flutters down slowly, striking the bottom at a considerable interval after the coin. See Fig. 111 *a*. When the air is pumped from the tube and it is again inverted, both fall simultaneously, Fig. 111 *b*. A man who weighs 200 lb. does not fall any faster than a man who weighs only 140 lb. A laboratory device known as the water hammer is sometimes used to demonstrate the same fact. It consists of a glass tube partly filled with water; the air is removed and the tube sealed. When the tube is jerked suddenly, the water falls like a stone, producing a sharp click as it strikes the glass.

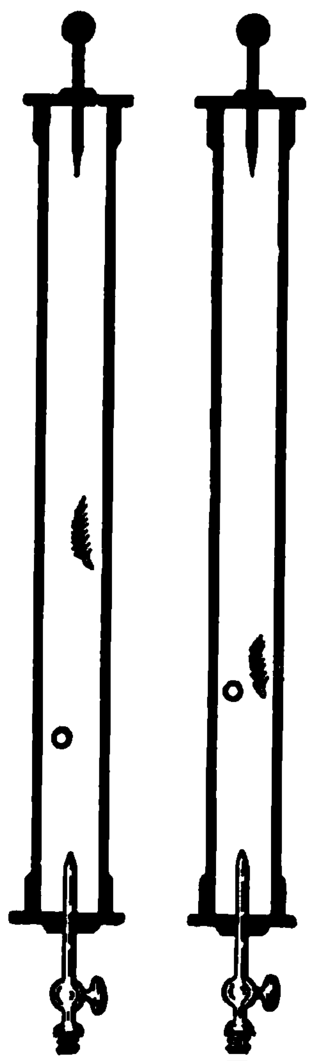



FIG. 111.—Bodies fall at same rate in vacuum.

**128. Bodies Projected Upward.** An object thrown upward is uniformly retarded until it finally stops rising. Then as it falls it is uniformly accelerated. If we know the initial velocity with which it is projected upward, we may apply the laws of accelerated motion to find how high it will rise, and how long a time will be required for the ascent.

PROBLEM. An object is projected upward with a velocity of 100 m. per sec. How high will it rise? How long a time will be needed for the ascent? How long a time will elapse before it strikes the earth?

*Solution.* In the formula, $v=\sqrt{2gS}$, $v$ and $g$ are known; $g=980$ cm. per sec., or 9.8 m. per sec. Substituting, $100=\sqrt{2\times 9.8\times S}$, whence $S=510.2$ m. From the formula, $v=gt$, we find the time required for the ascent, since $v$ and $g$ are known. Substituting, $100=9.8t$, whence $t=10.2$ sec. Since it takes the same time for it to fall, it will be 20.4 sec. before it strikes the earth.

## QUESTIONS AND PROBLEMS

1. Why does a parachute descend so slowly?

2. Give a reason why you would expect an object at the top of a high mountain to fall more rapidly than at its base. Give a reason why you would expect it to fall less rapidly.

3. A man runs 100 yd. in 10 sec. At that rate how long would it take him to run a mile? One kilometer?

4. A train 200 yd. long runs 60 mi. per hr. How long will be required for it to pass completely over a bridge 680 ft. long?

5. How far will a body fall in 4 seconds? In $\frac{1}{2}$ second? In $\frac{1}{4}$ second?

6. How far will a body fall in the seventh second? In 7 seconds?

7. A baseball is dropped from the top of Washington Monument 504 ft. With what velocity does it strike the earth? Do you think it is possible for a player to catch a baseball moving at this velocity? Has the feat ever been accomplished?

8. With what velocity must an object be thrown upward to make it rise to the top of the Woolworth building? (About 800 ft.)

9. A train is running 60 mi. per hr. If the maximum retardation of the brakes is 5 ft. per second, can the engineer stop the train within 600 ft.?

10. An airplane traveling 100 mi. per hr. drops a bomb from a height of 1500 ft. How long will it take for the bomb to fall? How far beyond the vertical line from which it was dropped will it strike the earth? (Consider that the bomb also moves horizontally at a speed of 100 mi. per hr.)

### *B.* THE PENDULUM

**129. The Pendulum.** A pendulum is a body so suspended that it can swing to and fro about a horizontal axis. A simple pendulum is defined as a particle suspended by a weightless cord. Of course it is impossible to construct such an ideal pendulum, but a ball suspended by a light thread, as shown in Fig. 112, is essentially a simple pendulum. The

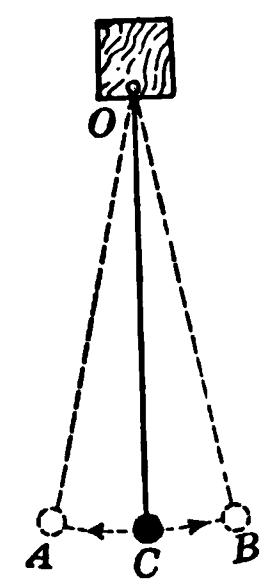



FIG. 112. — Simple pendulum.

point or axis about which a pendulum vibrates is called the *center of suspension*. As the ball moves from $A$ to $B$ it makes a *single vibration*. In moving from $A$ to $B$ and returning again to $A$, it makes a *complete vibration*. The time required for a complete vibration is known as the *period* of the pendulum. The angle $AOC$ is called the *amplitude* of vibration.

**130. Laws of the Pendulum.** Galileo noticed that the oscillations of a chandelier in the Cathedral at Pisa were made in equal times. Later he performed a series of experiments by which he ascertained several facts concerning the vibrations of the pendulum. They may be summarized as follows:

1. *The time of vibration is independent of the weight or material of the pendulum.*

2. *The time of vibration is independent of the amplitude, if the arc is small.*

3. *The time of vibration is directly proportional to the square root of the length of the pendulum.* This law may be expressed algebraically as follows:

$$t : t' = \sqrt{l} : \sqrt{l'}.$$

If it takes a pendulum 100 cm. long 1 sec. to make a single vibration, it will take a pendulum 25 cm. long just $\frac{1}{2}$ sec. to make a single vibration, since $1 : t' = \sqrt{100} : \sqrt{25}$; $t'$ equals 0.5 sec.

4. *The period of vibration is inversely proportional to the square root of the acceleration due to gravity.* A pendulum vibrates rather more rapidly at the North Pole than at the equator. If we use the letter $l$ to denote the length of a pendulum, and $g$ to denote the acceleration due to gravity, then $t$, the time required for a single vibration, may be found by the following formula: $t = \pi\sqrt{\frac{l}{g}}$.

**131. Center of Oscillation.** The length of the pendulum shown in Fig. 113 *a* is measured from the point of suspension

to the center of gravity of the ball *B*. A meter stick *CD* suspended from one end by a hook, although apparently the same length as the pendulum *a*, does not vibrate at the same rate. It is a *compound* pendulum, Fig. 113 *b*. Since its weight is distributed along its length, the several parts tend to vibrate as pendulums of different lengths. The particles near the lower end would, if isolated from the rest, vibrate more slowly. It is possible to find an intermediate particle, however, that would vibrate at the same rate as the undivided meter stick. This particle is at the *center of oscillation*. Experiment shows that the meter stick will vibrate at the same rate as the simple pendulum *P*, which is $\frac{2}{3}$ its length. If we bore a hole through the meter stick at the center of oscillation and suspend the meter stick from this point, it will have the same period as before. The real length of the meter stick swinging as a pendulum is the distance between the center of suspension and the center of oscillation.

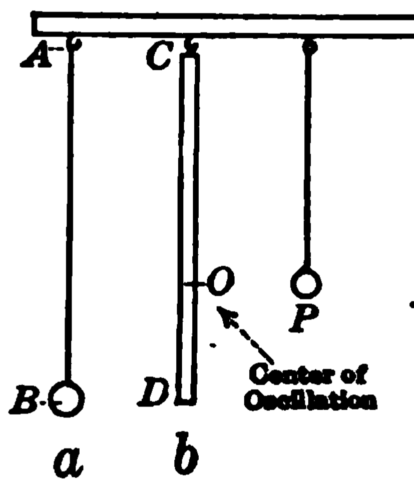


FIG. 113. — Compound pendulum.

**132. Center of Percussion.** If we strike the meter stick at its center of oscillation with a mallet when it is suspended as in Fig. 113 *b*, it will swing smoothly as a pendulum, without being jarred. If the meter stick is struck at any other point, it shivers or trembles instead of vibrating freely. The center of oscillation is coincident with the *center of percussion*. The center of percussion of a body is that point where a blow produces the least effect upon the center of suspension. A baseball player can drive a ball harder and farther if it strikes the bat at the center of percussion. If the ball strikes the bat at any other point, the bat "stings" the hands and is more apt to be broken. See Fig. 114.

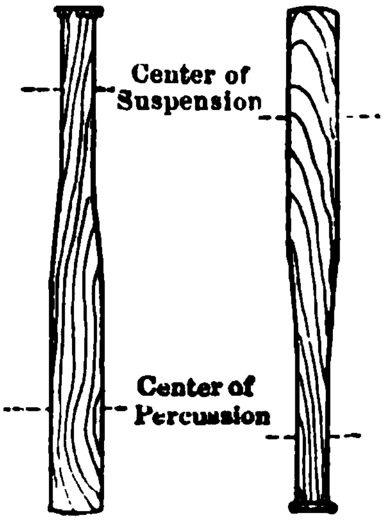



FIG. 114. — Center of percussion.

**133. Uses of the Pendulum.** The chief use of a pendulum is for keeping time. In a clock the movement of the hands is controlled by the swinging of a pendulum. In Fig. 115 the escapement wheel *W* is one of a train of gear wheels that move the hands. While these wheels are driven by a weight or spring, yet the escapement wheel is released one cog at a time by the vibrating pendulum, which thus indirectly controls the movement of the hands. A slight push from each cog as it escapes keeps the pendulum vibrating. A pendulum can be used to measure altitudes, but the barometer is more convenient.

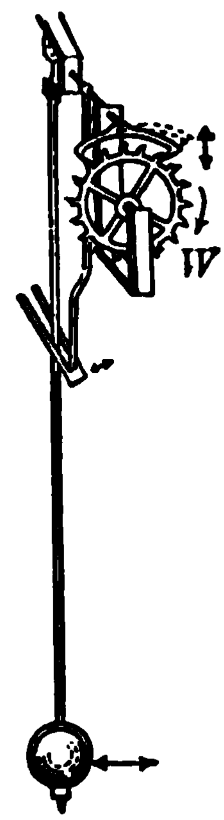



FIG. 115. — Clock pendulum.

## C. NEWTON'S LAWS OF MOTION

**134. Newton's Laws of Motion.** Sir Isaac Newton formulated three laws of motion that help to explain some very important principles of physics. While they are not capable of complete demonstration, yet observation and experiment furnish evidence of their truth as applied to the motion of both terrestrial and celestial bodies. We have already seen *how* bodies move; Newton's laws explain *why* bodies move. They deal with the relation between force and motion.

**135. Newton's First Law.** *Every body continues in its state of rest or uniform motion in a straight line unless it is compelled by some external force to change that state.* This law is really a statement of the property of inertia, which was discussed in § 12. No inanimate body can move or stop moving. A horse must pull very much harder to start a heavy load than to keep it moving; when started, how-

ever, it continues to move unless a backward force is applied to stop it. That an object tends to continue in motion in a *straight* line is clearly shown by the fact that mud flies from a rapidly rotating carriage wheel, or water from a grindstone along a line tangent to the circumference.

**136. Momentum.** Momentum may be defined as the quantity of motion. The momentum of a moving body is the product of its mass times its velocity. A mass of 1 gm. moving with a velocity of 1 cm. per sec. has one unit of momentum. A mass of 1 lb. moving with a velocity of 1 ft. per sec. has one unit of momentum. A 2000-ton boat moving with a velocity of 20 ft. per sec. has a momentum of 80,000,000 units (F.P.S.).

**137. Second Law of Motion.** *Rate of change of momentum is proportional to the acting force, and takes place in the direction in which the force acts.* Newton's first law states what happens to matter when forces *do not* act upon it; his second law states what happens when forces *do* act upon it. If a force acting upon a body produces a certain acceleration, doubling the force will double the acceleration. That is, the change of momentum is proportional to the acting force. Experience teaches us that motion is always in the same direction as that of the force which produces it. From this law of motion, the *dyne may now be defined as that force which, acting for one second upon any mass, imparts to it unit momentum.*

When two or more forces act together, each produces its own change of momentum, independently of the other forces. Thus the force that drives a bullet in a horizontal direction acts continuously; at the same time the force of gravity is gradually pulling the bullet toward the earth. A ball dropped from the top of a tall tower strikes the ground at the same instant as a bullet fired horizontally from the top of the tower, although the latter may fall several thousand feet distant. See Fig. 116.

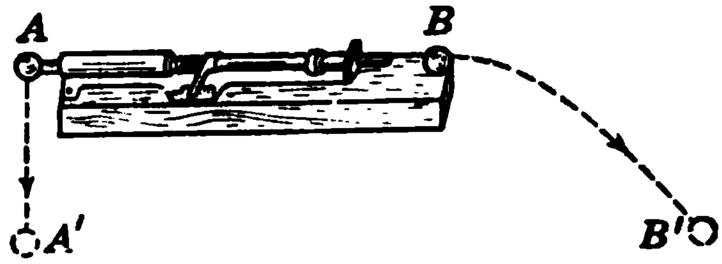



FIG. 116. — Both balls strike the floor at the same instant.

**138. Composition of Velocities.** From the preceding paragraph it is evident that physics deals with the composition of velocities as well as with the composition of forces. Since the action of a force imparts to a body its velocity, and different forces acting upon the same object are independent of one another, we may represent velocities graphically and determine their resultant in exactly the same manner that we plotted component forces.

**139. Path of a Projectile.** (*a*) *Fired horizontally.* Many persons have the idea that a rifle bullet fired horizontally travels in a straight line, but such is not the case. Gravity acts upon it immediately and constantly, pulling it from its course. Suppose its velocity is 3000 ft. per sec.; at the end of the first second, air resistance being ignored, it will have traveled 3000 ft.; but in 1 second a body falls 16.08 ft., and the bullet would strike 16.08 ft. below the point at which it was aimed. In 2 seconds the bullet travels 6000 ft., but it drops in the same interval 64.32 ft. See Fig. 117 *A*. Of course, the greater the velocity, the more nearly the curve approaches a straight line. The curve of Fig. 117 *B* shows the path of a ball thrown with a horizontal velocity of 100 ft. per second.

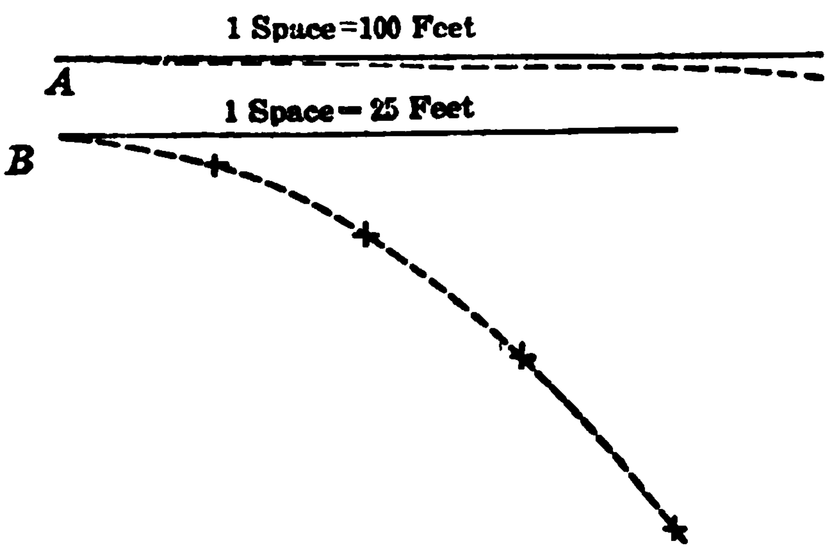



FIG. 117. — *A*. Curve of high velocity projectile. *B*. Curve of low velocity projectile.

(*b*) *Fired at an angle.* In the use of the modern rifle, in which the bullet may have a velocity of 3000 ft. per second,

the path of the bullet is so nearly horizontal that no correction need be made for *short* distances. When the object is more remote, the rear sight of the rifle is raised a trifle. When the rifle is then aimed at an object, the end of the barrel is raised slightly. The farther away the object, the more the rear sight is elevated before taking aim. The muzzle of a field gun is always elevated so that the projectile is fired at an angle. Fig. 118 shows the path such a projectile may take. The angle $BAC$ is the *angle of elevation.* $AC$ and $AD$ are the component horizontal and vertical velocities, and $AR$ is the *range.* The path $ABR$ is called the *trajectory.* The higher the velocity of the projectile, the flatter the trajectory, Fig. 117. Under actual conditions, air resistance reduces the range, and corrections must be made for windage.

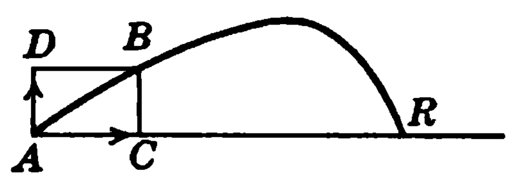


FIG. 118. — Path of projectile, fired at an angle.

**140. Newton's Third Law.** *To every action there is an equal and opposite reaction.* The end of a garden hose is pushed backward by the reaction of the water as it issues from the nozzle. The rotary lawn sprinkler works on the same principle. As the water issues from the nozzles, the rotating head is turned backward, thus scattering the water in all directions. A boy who wishes to jump forward must stand on something fixed. If he tries to leap ashore from a rowboat, the boat is pushed backward, while the boy misses his mark and falls into the water. Water reacts against the oars of a boat, and its reaction against the propellers makes the movement of a steamboat possible. The reaction of the air against the wings of a bird enables it to fly. The air reacts against the propellers of an airplane as they drive it forward, and the reaction of the air against the planes is resolved into two forces, one of which lifts the plane upward, Fig. 98. The "kick" or recoil of a gun is an example of reaction. The recoil may be used to eject

FIG. 119. — This disappearing gun can hurl a 16-inch projectile through 14 in. of armor plate steel. Its recoil energy is 4000 foot-tons. The gun, which is 70 ft. long, is mounted in a "barbette" housing. (*Times Photo*)

the empty cartridges in rapid-fire guns; it is also used in *disappearing* guns for coast defense, where the recoil carries the gun back on its carriage and down behind the fortifications. Fig. 119.

The collision balls of Fig. 120 show that the force of reaction is *equal* to the action. If one ball is raised and then let fall, one ball flies out at the opposite end of the line. When two balls are let fall, two balls at the other end of the line move in response to their action. In all cases, action is equal to reaction.



FIG. 120. — Action equals reaction.

## *D.* CURVILINEAR MOTION AND CENTRIFUGAL FORCE

**141. How Curvilinear Motion Is Produced.** From Newton's first law we learned that a body which has acquired velocity continues to move in a straight line. If a second force acts upon the moving body at right angles to its path, it will be deflected from its rectilinear line, its motion becom-

ing curvilinear. To illustrate, we may tie one end of a string to a ball. Holding the other end firmly, we may swing the ball in a circle about the hand as a center. The pull the hand exerts upon the cord deflects the ball toward the center and away from its rectilinear path, Fig. 121. If the cord breaks, the ball continues in a straight line tangent to the curve. The constant pull that deflects a body from its rectilinear path, and compels it to move along a curve, is called *centripetal force.*

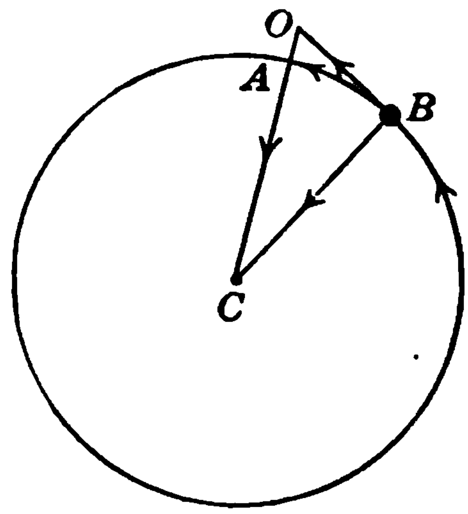


FIG. 121. — Curvilinear motion.

If the body did not have inertia, it would be pulled to the center. The reaction due to its inertia, which the moving body offers to the centripetal pull, tends to break the string and permit the body to resume rectilinear motion. *The resistance that a moving body offers to deflection from a straight line is known as centrifugal force.*

**142. Magnitude of Centrifugal Force.** If we use a ball whose mass is double that of the ball used in the preceding experiment, the pull on the string will be just twice as great. *The centrifugal force is directly proportional to the mass.* If we shorten the string, the ball is pulled from its path faster and it reacts with greater force to break the string. Hence, *centrifugal force is inversely proportional to the radius of curvature.* As we swing the ball faster, so that the velocity along the curve increases, it pulls more strongly on the cord. Accurate measurements show that the *centrifugal force is directly proportional to the square of the velocity.* Let $v =$ velocity in centimeters per second, $m$ the mass in grams, and $r$ the radius in centimeters. Then the centrifugal force (C.F.) in dynes may be found by the following formula:

$$\text{C.F.} = \frac{mv^2}{r}. \quad \text{C.F. (in gm.)} = \frac{mv^2}{gr}.$$

In the English system, if the mass is in lb., the radius in ft., and the velocity in ft. per sec., the centrifugal force in poundals may be found by the above formula. Poundals may be changed to pounds by dividing by 32.16.

**143. Illustrations of Centrifugal Force.** Mud flies from a rotating carriage wheel when the centrifugal force exceeds its adhesion to the tire. Emery wheels sometimes burst

FIG. 122. — The Velodrome track at Newark, N. J., is banked at the turns to counteract centrifugal force.

when driven at a high velocity; the centrifugal force exceeds cohesion. An automobile rounding a curve at high speed is apt to turn "turtle."

We lean toward the center when skating around a curve, to prevent being thrown over by centrifugal force. To prevent the overturning of a railway train rounding a curve, the track is banked so that the rails on the outside of the curve are higher than the inside rails. The running track in a gymnasium is banked at the curves to help the runners overcome centrifugal force. Race-courses are banked for the same purpose. See Fig. 122.

**144. Practical Applications.** In a *cream separator*, the milk is thrown against the lower surfaces of the rapidly rotating blades. See Figs. 123 and 124. The skim milk passes on to the outside of the rotating blades, where it is drawn off, while the lighter cream rises along the top surfaces of the blades and issues from an opening near the center. See Fig. 125. The *governor* on a stationary engine is operated by centrifugal force. If the engine runs too fast, the governor balls, Fig. 126,


FIG. 123. — Cream separator blades.

rise by centrifugal force and partially shut off the supply of steam. Wet solids may be partially dried by putting them in a perforated cylinder, which is then rapidly rotated. The water is thrown out through the openings. Laundries use this method for drying clothes; crystals are often dried in this manner. See Fig. 127. Liquids that contain sediment are often centrifuged instead of being filtered. The "human pool table" at Coney Island is another application. A very efficient water pump depends for its action upon centrifugal force, Fig. 128. As the rotor turns rapidly in the direction shown by the arrows,

FIG. 124. — The milk enters at the top and is separated by centrifugal force. These blades or discs rotate at a speed of from 6000 to 8000 revolutions per minute. The skim milk, which is heavier, is thrown outward against the lower surface of the discs, whence it passes down to the outer edge of the bowl. The cream, being lighter, passes upward and inward to the center.

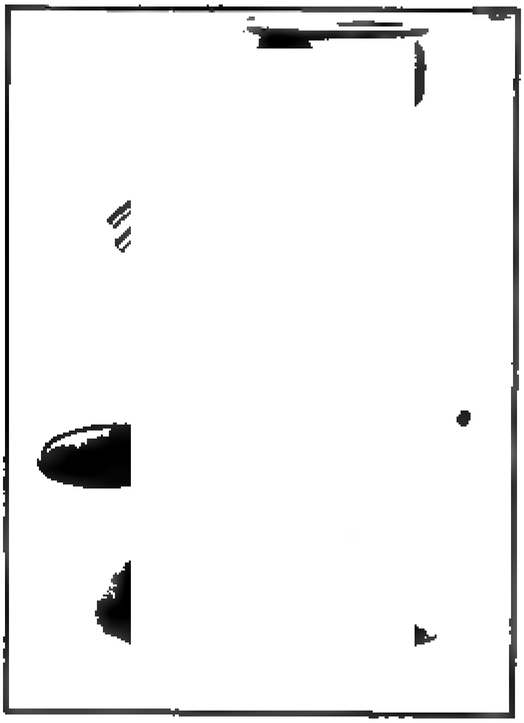


Fig. 125. — Cream separator.

the water is forced by the rotating blades out through the discharge pipe.

**145. The Gyroscope.** Every one is familiar with the toy gyroscope and the spinning top. The centrifugal force of a heavy, rotating wheel gives it great stability. When such a wheel is rotating rapidly in a certain plane, considerable force must be used to change the plane of rotation. The principle of the gyroscope has been put to practical use in many ways. The Sperry type of stabilizer used on airplanes depends upon this principle. A gyroscopic compass is now used on all submarines. In the monorail cars stability is secured by a pair of gyroscopic wheels rotating in opposite directions on axes that extend across the car. The flywheels on the engines of a steamship are mounted in this manner; thus they tend to prevent the rolling of the ship.

Fig. 126. — Centrifugal force regulates speed of steam engine.

### *E.* FRICTION

**146. Friction.** Friction opposes motion. *We may define friction as the resistance that opposes any effort to roll or slide one body over another.* It is largely caused by irregularities in the surfaces

of the bodies. To some extent it is due to adhesion.

**147. Sliding Friction.** Since there are so many varying conditions under which friction occurs, the so-called laws of sliding friction are only approximately correct. Experiments show: (1) That friction is greater at starting; when a body is in motion, friction is nearly independent of velocity, although it is slightly greater when the velocity is slow. (2) Sliding friction is practically independent of the area of contact between the surfaces. A brick offers nearly the same resistance when sliding on its side that it does when sliding on its edge. (3) Friction is directly proportional to the weight of the object. It does not require so much force to slide an empty chair across the floor as it does if a 200-lb. man sits on the chair.

FIG. 127. — Centrifugals are used to dry clothes, crystals, etc.

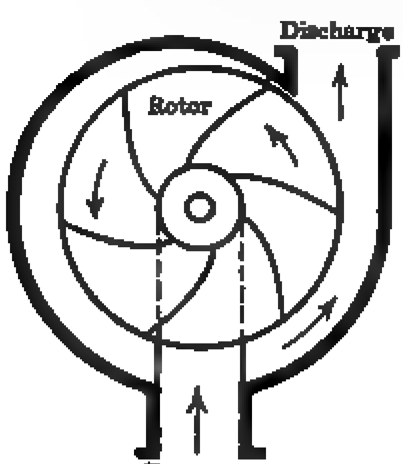


FIG. 128. — Centrifugal pump.

**148. Coefficient of Friction.** The coefficient of friction may be found by the use of an apparatus similar to that shown in Fig. 129. The force required to keep the block *B*

moving uniformly may be found by a spring balance; the weight of the block may also be determined. The coefficient of friction for the two surfaces is the ratio of the "force of friction" to the weight. Suppose 30 gm. are required to keep a 100-gm. weight in uniform motion; the coefficient of friction is $\frac{30}{100}$, or 0.3.

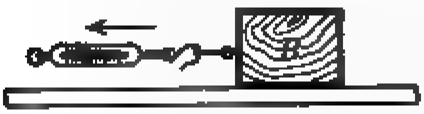


Fig. 129. — Sliding friction.

The coefficient of friction varies with the nature of the material and the degree of polish of the surface. The coefficient of friction for iron on iron is less than that for wood sliding on wood.

**149. Advantages and Disadvantages of Friction.** In cases where an object is to be moved or a resisting force is to be overcome, friction is a disadvantage. In the bearings of machinery, every effort is made to reduce friction. In many cases, however, an acting force is useless without friction. A horse cannot pull a load unless friction furnishes him a secure foothold. The friction between the drive-wheels of a locomotive and the rails makes it possible to start the train. If this friction is sufficiently reduced, the drive-wheels spin around, but the train does not move. Sand is often added to the track to increase the friction. Chains are put on the rear wheels of automobiles to enable the tires to "grip" the pavement without "skidding." Without friction we would be unable to walk, for even the smoothest ice has some friction. Without friction a nail or screw, driven into a board, could readily be removed with the fingers; from the ceilings nails would fall of their own weight.

Fig. 130. — Ball bearings.

**150. Fluid Friction.** Every one knows that a wet pavement is more slippery than a dry one. It is generally true

that fluid friction is much less than solid friction. While solid friction is practically independent of velocity, fluid friction increases with an increase of velocity. For low speeds the increase is nearly proportional to the square of the velocity; at higher speeds it is proportional to the cube of the velocity, or nearly so. It is not economical to run a boat at high speed, since the friction in plowing through the water increases so rapidly with increased speed. The same is true of the air resistance when trains or automobiles are run at high speed.

FIG. 131. — Flexible roller bearings. See also Fig. 539.

**151. Methods of Reducing Friction.** Several methods of reducing friction are in common use. (1) The surfaces of bearings are made of highly polished material. (2) Bearings are often packed with Babbitt metal, an alloy that has a very low coefficient of friction. It is sometimes called anti-friction metal. (3) Ball bearings, or roller bearings, are often used, since rolling friction is decidedly less than sliding friction. See Figs. 130 and 131. Rolling friction is especially low if both surfaces are hard. When one sinks into the other, as a carriage wheel into a sandy road, then

rolling friction may be very great. Fig. 132 shows the tapered roller bearings which are used on many automobiles. They are especially strong in resisting sidewise thrusts. (4) Lubricants are used to reduce friction. Some of the most common lubricants are oils, grease, and graphite. Paraffin and soap are good lubricants for wood. When oil,

FIG. 132. — Tapered roller bearings. See also Fig. 538.

for example, is used as a lubricant, an oil film flows between the surfaces of the bearing, separating them so that fluid friction is substituted for solid friction. A good lubricant must have just body enough so that it will not be squeezed out of the bearing by the weight of the parts; it must not evaporate readily; it must not corrode the bearings; and it must be free from hard, gritty substances.

## SUMMARY

Motion may be rectilinear or curvilinear. Velocity is the rate of motion. Acceleration is the rate of change of velocity.

If the acceleration is constant, velocity = acceleration $\times$ time; space passed over $= \frac{1}{2}at^2$.

The laws of accelerated motion apply to uniformly retarded motion. Freely falling bodies are uniformly accelerated. The acceleration, which is due to gravity, is approximately 980 cm. per second.

The period of vibration of the pendulum is independent of the mass, material, or amplitude; it is directly proportional to the square root of the length, and inversely proportional to the square root of the acceleration due to gravity.

Newton formulated three laws of motion: Every body continues in its state of rest or uniform motion in a straight line unless compelled by some external force to change that state. Rate of change of momentum is proportional to the acting force and takes place in the direction in which the force acts. For every action there is an equal and opposite reaction.

Momentum is the quantity of motion. It equals the product of the mass times the velocity.

Centrifugal force increases with the mass; it is directly proportional to the square of the velocity; it is inversely proportional to the radius of curvature.

Friction, or the resistance to motion, is generally greater in solids than in fluids. Lubricants are used to reduce friction.

## QUESTIONS AND PROBLEMS

1. If a clock gains time, would you raise or lower the pendulum bob?

2. Does a pendulum vibrate faster at the top of a mountain or at its base?

3. In which case can a boy throw a 12-lb. hammer farther, if a 4-ft. or a 3-ft. wire is attached? Explain.

4. If a man is strong enough to swing a 5-ft. baseball bat, can he drive a ball farther than with a bat of the usual length? If so, why not use such a bat?

5. Other things being equal, does a long-armed baseball pitcher have an advantage over a shorter-armed opponent?

6. How do the bicycle and the motor-cycle illustrate the gyroscopic principle?

7. How would you locate the center of percussion of a baseball bat?

8. A hammer sometimes "stings" the hand. Explain.

9. Is the range of a field gun increased by increasing its angle of elevation?

10. Which has the greater momentum, a 175-lb. man running with a speed of 25 ft. per second, or a 160-lb. man running with a speed of 30 ft. per second?

11. Why do farm wagons often have tires from 3 to 5 inches wide?

12. Explain the principle of the rotary lawn sprinkler.

13. Why is the head of a hammer tightened by pounding on the end of the handle?

14. How does centrifugal force affect the weight of objects at the equator?

15. Why is it not as dangerous to receive the "kick" of a rifle as to be struck by the bullet, if action equals reaction?

16. If a pendulum 100 cm. long makes a single vibration in 1 sec., how long will it take for a pendulum 64 cm. long to vibrate?

17. How long must a pendulum be to make a single vibration in 1 sec., if $g$ equals 980 cm. per second?

18. If the coefficient of friction between the drive-wheels of a locomotive and the rails is 0.2, what must be the weight of an engine that is to exert a pull of 400 tons? How would the pull such an engine is capable of exerting be affected if the coefficient of friction is increased to 0.4 by sanding the track?

19. If a force of 20 lb. keeps a 2000-lb. roller moving, what is the coefficient of friction?

20. A ball weighing 12 lb. is swung in a circle by a cord 4 ft. long. If its velocity is 20 ft. per sec., what pull does it exert on the cord?

21. A car weighing 2400 lb. rounds a curve of 60 ft. radius at a velocity of 45 mi. per hr. What is the force tending to overturn it? Will the car "turn turtle"?

*Suggested Topics.* Work of Galileo. Sir Isaac Newton. Gyroscopic Compass.

## CHAPTER 7

# WORK — POWER — ENERGY

### *A.* WORK

**152. Work.** When a force acts upon a body in such a way that the body is moved, it is said to do work upon the body. A man pulling at a 2000-lb. safe does no work unless he moves the safe. If a man holds a weight of 100 lb. on his shoulder all day, he is exerting force, but in the *scientific sense* he is not doing any work. He does work when he lifts the weight to his shoulder. *The amount of work done is the product of the force times the distance through which it acts.* This definition of the term " work " is quite different from

**FIG. 133. — Gigantic cranes unload 10,000 to 13,000 tons of iron ore in four or five hours.**

the usual conception of the word. Usually a man is not paid for his *effort*, but for the *effect produced*, or the *work accomplished.* A student is graded upon the task accomplished and not upon his efforts. The ore crane shown in Fig. 133 works rapidly, since it can remove 15 tons of ore per bucketful. Boats containing 13,000 tons have been unloaded in 4½ hours with the modern unloaders. See Fig. 134.

Fig. 134. — Clam-shell buckets of ore unloaders hold from 10 to 15 tons of ore.

**153. Units of Work.** (*a*) *Gravitational units.* In the Metric System the gravitational units of work are the *gram centimeter* and the *kilogram meter*. The names practically define themselves. The gram centimeter is the amount of work done by one "gram of force" when it moves the body upon which it acts a distance of one centimeter. The

kilogram meter is the amount of work done by a force of one kilogram acting through a distance of one meter.

In the English System the *foot pound* is the gravitational unit. The foot pound is the amount of work done by one "pound of force" acting through a distance of one foot. A man weighing 160 lb. does 1600 ft. lb. of work in climbing a flight of stairs 10 ft. high. He lifts his own weight 10 ft. against the force of gravity. When an object is lifted vertically, the amount of work done always equals the weight of the object times the vertical height through which it is lifted.

(*b*) *Absolute units.* Three absolute units of work are in use, the *erg*, the *joule*, and the *foot poundal.* The erg is the amount of work done by a force of one dyne acting through a distance of one centimeter. Since the erg is a very small unit, the joule is more often used. The joule, named in honor of a great English physicist, James Prescott Joule, is equal to 10,000,000 ergs, or $10^7$ ergs. The amount of work done by a force of one poundal acting through a distance of one foot is called a foot poundal.

## *B.* POWER

**154. Power Defined.** *Power is the rate of doing work. Force* is independent of both time and distance. The amount of *work* done equals *force times distance,* but it is wholly independent of time. A man does the same amount of work when he climbs a flight of stairs in 1 minute that he does when he climbs the same flight in 5 minutes. *Power depends upon all three factors: the force exerted, the distance it moves, and the time required.* Here again, the student must revise his conception of the word "power." We are accustomed to speak of a "powerful" man when we mean that he is strong and capable of exerting great force. He may work so slowly that his power in a scientific sense is very small.

**155. Units of Power.** In a series of experiments, James Watt, the inventor of the steam engine, found that an English dray horse could continue for a reasonable length of time to do 550 ft. lb. of work per second. More recent experiments show that the average horse has only about $\frac{2}{3}$ this power, but the value of the horse power is still based upon Watt's experiments. In the English System the *horse power* is the unit of power; it is equal to 550 ft. lb. of work *per second*, or 33,000 ft. lb. of work *per minute*. Engines in this country are rated in horse power, or in kilowatts.

FIG. 135. — The Virginian locomotive is the largest in the world. During a test on May 25, 1921, this locomotive pulled a solid train of one hundred 120-ton gondola cars, loaded to capacity, a total weight of 16,000 gross tons. The engine weighs 450 tons; its horse power is 5100. It uses one ton of coal every ten minutes, the coal being fed by a mechanical stoker.

The ordinary railroad locomotive has a horse power of 500 to 1000. See Fig. 135. The power of the average man is about $\frac{1}{4}$ horse power.

The *watt* and the *kilowatt* are units of power used in the Metric System. *The watt is equal to one joule per second. The kilowatt (K.W.) equals 1000 watts.* The horse power (H.P.) is equivalent to 746 watts, or nearly $\frac{3}{4}$ of a kilowatt. For example, a 15 K.W. engine is approximately 20 H.P.

PROBLEM. What horse power engine is required to hoist 100 tons of coal per hr. from a mine 200 ft. deep?

**Sir William Thomson** (Lord Kelvin) (1824–1907) was an English physicist. His most important contributions to physics were in heat and electricity. He invented the absolute scale of temperature. His other inventions include the mirror galvanometer, the siphon recorder for use in receiving cable signals, and an improved mariner's compass. Thomson combined mathematical ability with inventive genius.

**James Watt** (1736–1819) was a Scotch engineer. Watt is considered as the inventor of the steam engine. He improved the old Newcomen engine by adding valves to make it double acting, and by using an external condenser. His inventions include the centrifugal governor, the water and steam gauges, and the steam hammer. He made the first compound engine. The metric unit of power is called the watt in his honor.

*Solution.* Horse power $= \dfrac{\text{total work done (in ft. lb.)}}{550 \times \text{time in seconds}}$.

Then, horse power $= \dfrac{100 \times 2000 \times 200}{550 \times 60 \times 60}$ ; the answer is 20.2 H.P.

## PROBLEMS

**1.** How much work would you do in climbing a flight of stairs 20 ft. high? What is your horse power, if you run up the stairs in 10 seconds? Suppose you can climb the stairs in 10 seconds or less; would the results show that ¼ H. P. is too low an estimate for the average man power?

**2.** If a horse pulls with a force of 240 lb. to keep an 800-lb. wagon moving, how much work does he do in pulling the wagon ¼ mile? If he pulls the wagon at the rate of 2 mi. per hr., what horse power does he use?

**3.** If each of the citizens of a city of 400,000 inhabitants uses 5 gallons of water (40 lb.) daily, what H.P. engines must be used if the height to which the water must be pumped is 100 feet?

**4.** The express elevator in the Woolworth building makes the ascent to the tower in one minute. If the distance is 750 ft., what H.P. is used in lifting a 200-lb. man to the tower?

**5.** What H.P. would you use in climbing a mountain 2500 ft. high in 30 minutes? Since you could probably walk 4 times that far in 30 minutes, give a reason why mountain climbing is so slow and fatiguing.

## *C.* ENERGY

**156. Energy Defined.** *Energy is the capacity for doing work.* An inorganic body has energy, if work has been done in lifting it to some elevated position or in imparting to it velocity. Flowing water has energy because the pull of gravity has given it velocity. Wind is a similar example. Steam has expansive force; hence it is able to exert pressure and do work. A weight lifted to an elevated position has had work done upon it; it has energy of position. Heat, light, electricity, and mechanical energy are some of the types of energy with which physics deals.

**157. Kinds of Energy.** Energy is of two kinds, *kinetic* and *potential*. *Kinetic energy is energy of motion;* a body has kinetic energy due to its velocity. A moving cannon ball, strong winds, falling and running water are all examples of kinetic energy. *Potential energy is stored energy, or energy of position.* A rock resting on a precipice has potential energy; if it falls over the edge, its energy becomes kinetic. A coiled spring has potential energy. Work was done in winding the spring; as it unwinds, its energy becomes kinetic. Gasoline has potential energy. When a mixture of gasoline vapor and air explodes, it is capable of doing work. Potential energy may be transformed into kinetic, or vice versa.

**158. Measurement of Energy.** The units of work are also used in measuring energy. If we lift a weight of 40 lb. from the floor to a table 3 ft. high, we do 120 ft. lb. of work. The weight has thus acquired 120 ft. lb. of potential energy. In falling to the floor, it is capable of doing 120 ft. lb. of work. Hence we say that potential energy equals $mh$. If the mass $m$ is expressed in gm., and the height $h$ in centimeters, then the potential energy will be expressed in gm. cm. We may write: P.E. (in ergs) $= mgh$, in which $g$ equals 980 cm. per second.

If the velocity of a body is given, its kinetic energy may be found by the use of the following formula: K.E. (in ergs) $= \frac{1}{2}mv^2$. Dividing the result by 980 gives the kinetic energy in gm. cm.

In the expression $mgh$, we may substitute for $h$ its equivalent $S$, as used for accelerated motion. Then we learned that $v = \sqrt{2gS}$, whence $S = \frac{v^2}{2g}$. Substituting, K.E. $= mg \times \frac{v^2}{2g}$; and K.E. $= \frac{1}{2}mv^2$.

A bullet having a mass of 50 gm., moving with a velocity of 3000 m. per sec., has a kinetic energy of $25 \times (300{,}000)^2$ ergs. The result is $225 \times 10^{10}$ ergs. Dividing this result by 98,000,000 $(980 \times 1000 \times 100)$ gives the result in Kgm. m. of energy. In the English System, K.E. (in foot poundals) $= \frac{1}{2}mv^2$, if $m$ is expressed in

lb., and $v$ in ft. per sec. Dividing the result in foot poundals by 32.16 gives the result in ft. lb.

**159. Conservation of Energy.** Like matter itself, energy can neither be created nor destroyed. There is the same amount of energy in the universe to-day that there was yesterday, and the amount will be unchanged to-morrow. These facts show why the *output* of a machine can never exceed the *input*. A perpetual motion machine is utterly impossible. Even if friction and the weight of the parts could be eliminated, the machine could never create energy; it would never have any more energy than was put into it.

**160. Transformations of Energy.** Although energy cannot be created, it can be transformed from one kind into another. We have already learned that it is possible to transform kinetic energy into potential energy, and vice versa. Heat energy can be transformed into mechanical energy, mechanical into electrical, and electrical into mechanical, heat, or light energy. Let us use just one concrete example. Heat from the sun evaporates water; some of this vapor, which is carried by winds, may fall as rain, into Lake Erie. Here its potential energy is transformed into kinetic as the water flows down Niagara River to the Falls. This transformation continues as it passes through the turbine pits and turns the large wheels at the bottom, thus producing mechanical energy. The turbines turn alternators which generate electricity. This electrical energy is transmitted to various places, where it is utilized for lighting, heating, or in the mechanical work of turning motors. In these cases heat energy is set free, either in doing useful work or in overcoming friction. This heat may evaporate more water to begin anew the energy transformations. During all these transformations the total amount of energy is unchanged. The fact that energy may be transformed or transferred, but cannot be destroyed, is known as the law of the *conservation of energy*.

## SUMMARY

When a force acts upon a body and produces motion, work is done upon that body. The gm. cm., Kgm. m., and ft. lb. are gravitational units of work. The erg, the joule, and the foot poundal are absolute units of work. One foot pound equals 32.16 foot poundals.

Power is the rate of doing work. The horse power, watt, and kilowatt are the units of power. The horse power equals 550 ft. lb. per second.

Energy is the capacity for doing work. The units of work are used to measure energy. Energy can neither be created nor destroyed. It may be transformed in practically any manner.

## QUESTIONS AND PROBLEMS

1. Find the potential energy of 1 cu. ft. of water at the top of Niagara Falls. (Height equals 164 ft.)

2. A projectile weighing 1000 lb. moves with a velocity of 2500 ft. per sec. Find its kinetic energy in foot poundals; in foot pounds; in foot tons.

3. If all the kinetic energy of problem 2 were transformed into work, to what height could the projectile be lifted? (Divide kinetic energy in ft. lb. by the weight of the projectile.)

4. Using the formula, $v=\sqrt{2gS}$, find out how high a body projected upward with a velocity of 2500 ft. per sec. would rise. Compare the result you obtain with the answer to problem 3.

5. A waterfall is 140 ft. high. If 1000 cu. ft. of water flow over it per second, what horse power can it develop?

6. An automobile weighing 3000 lb. climbs a hill that rises 8 ft. in 44 ft. of its length at the rate of 30 mi. per hr. What is the minimum horse power developed by the engine?

7. A pile-driver weighs 1000 lb. In falling 4 ft. how far will it drive a pile if the earth resistance is 6000 lb.?

# CHAPTER 8

# MACHINES

## *A.* DEFINITIONS — PRINCIPLES

**161. Machines.** A machine is a device used to transform or transfer energy. Machines are used *to increase the magnitude of a force, to increase speed,* or merely *to change the direction in which a force is applied.* A nail that cannot be pulled with the fingers may be drawn with a claw hammer used as a lever. By means of a jack-screw the axle of an automobile is lifted so that the wheel may be removed. Two men who wish to put a 2000-lb. safe into a wagon can do so quite easily if they roll it up a plank used as an inclined plane. A bicycle is a machine used to gain speed. It is easier to raise a flag to the top of a pole by the use of a rope passed over a pulley than to climb the flagpole. These illustrations serve to show a few of the varied uses to which machines are put.

**162. Simple Machines.** Six simple machines are usually discussed in physics: the *lever;* the *pulley;* the *wheel and axle;* the *inclined plane;* the *screw;* and the *wedge.* Other machines are either modifications of one of these simple machines, or combinations of two or more of them. It is also quite easy to show that the pulley and the wheel and axle are really levers, and that the wedge and the screw are inclined planes.

**163. General Law of Machines.** In this chapter we shall use the term "effort" ($E$) when we refer to the *acting force,*

and the term "resistance" ($R$) when we refer to the *resisting force*, or to the *weight* or *load* to be moved. Whenever friction is negligible, *the product of the effort times the distance the effort moves equals the resistance times the distance the resistance moves.* Using $De$ to represent the distance effort moves, and $Dr$ to represent the distance the resistance moves, then $E \times De = R \times Dr$. The effort times the distance it moves equals the work put into the machine, or *input;* the resistance times the distance the resistance moves equals work accomplished, or *output. Neglecting friction, input equals output.* When efficiency is considered, then work expended equals useful work accomplished plus work used to overcome friction, or *input equals useful work plus friction.*

**164. Mechanical Advantage.** *The mechanical advantage of any machine equals the ratio of the resistance to the effort,* or $\frac{R}{E}$; *it is also equal to the ratio,* $\frac{De}{Dr}$. If by the use of a machine 4 lb. of effort overcome a resistance of 20 lb., then the mechanical advantage of such a machine is $\frac{20}{4}$, or 5; this means that every pound of effort overcomes a resistance of 5 lb. Of course in doing so, the effort must move five times as far as the resistance is moved.

The ratios of the dimensions of certain parts of a machine can be used to express its mechanical advantage. When we studied the hydraulic press, we found that its advantage equals the ratio of the squares of the diameters of the two pistons. The term "mechanical advantage" (M.A.) is generally referred to a machine as if it operated without friction; it is what we might expect a machine to do from a theoretical standpoint.

**165. Efficiency.** It is impossible to eliminate friction entirely, and friction results in wasted work. Only a part of the energy put into a machine is utilized. *The efficiency of a machine is the ratio of the useful work accomplished to the total work expended.*

$$\text{Efficiency} = \frac{\text{useful work}}{\text{total work}}.$$

Efficiency is usually expressed in per cent. Suppose an effort of 40 lb. moves 20 ft. along an inclined plane and in so doing lifts a weight of 180 lb. to a height of 4 ft. The useful work done equals $4 \times 180$, or 720 ft. lb.; the total work equals $20 \times 40$, or 800 ft. lb. Then the efficiency equals $\frac{720}{800}$; dividing, we get a quotient of 0.90, or 90%. Suppose we have a machine that has a mechanical advantage of 5. A force of 20 lb. should support a weight of 100 lb. If actual experiment shows that 25 lb. of force are required to support 100 lb., then the efficiency of the machine is $\frac{20}{25}$, or 80%. Some machines are nearly frictionless. The efficiency of simple machines will be discussed after their mechanical advantage has been studied.

## *B*. LEVER

**166. The Lever.** The lever is a rigid bar free to move about a fixed point called the *fulcrum*; it may be straight or bent. *In all classes of levers the mechanical advantage equals the length of the effort arm divided by the length of the resistance arm.* In bent levers, the length of the arm is measured along a straight line drawn at right angles to the direction at which the force is applied to the fulcrum.

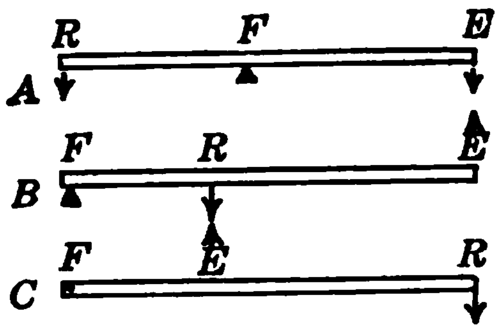


FIG. 136. — Three classes of levers.

Levers are of three classes, depending upon the position of the fulcrum. In the *first-class lever the fulcrum is between the effort and the resistance.* See Fig. 136 *a*.

$$\text{M.A.} = \frac{EF}{RF}.$$

When $EF$ and $RF$ are equal, the mechanical advantage is unity; then 1 lb. of effort at $E$ counterbalances 1 lb. of

resistance at $R$. The beam balance, Fig. 137, is a common example of such a lever. If such a balance is well constructed, the two arms are of equal length and the light, rigid beam rests upon a very hard knife-edge fulcrum. Very accurate weighings can be made with such a balance. When $EF$ exceeds $RF$, the mechanical advantage of the first-class lever is more than one; the common pump-handle and the tinner's shears are examples. When $RF$ exceeds $EF$, the advantage is less than one. Such a lever is used to gain speed. The tailor's shears furnish an example. Shears of nearly all kinds are double levers of the first class.

Fig. 137. — Beam balance.

In the *second-class lever the resistance is between the effort and the fulcrum,* which is generally at one end of the lever. See Fig. 136 *b*. Since $EF$ is greater than $RF$, the mechanical advantage of the second-class lever is always greater than unity. Generally $EF$ equals the whole length of the lever; by moving $R$ nearer the fulcrum, we shorten $RF$ and increase the advantage. If a lever is 6 ft. long and $R$ is placed 1 ft. from the fulcrum, the mechanical advantage is 6; 1 lb. of effort at $E$ will balance 6 lb. at $R$. When $R$ is 2 ft. from the fulcrum, the M.A. is only 3, and 2 lb. of effort will be needed to counterbalance 6 lb. at $R$. The wheelbarrow and the nut-cracker are examples of second-class levers. Review parallel forces.

If two boys carry a load on a pole between them, we may consider the pole a second class lever and one of the boys the fulcrum. Then it is easy to find the force the second boy must use to lift the load.

In the *third-class lever the effort is applied between the resistance and the fulcrum*, Fig. 136 *c*. Since *RF* is greater than *EF*, the mechanical advantage is less than one; the *mechanical advantage of speed, which is the inverse ratio of the advantage of force, is greater than one*. The resistance moves farther and faster than the effort. The third-class lever is used when speed is required. When lifting a weight on the hand, we use the forearm as a third-class lever. A fork, a shovel, or a broom may be used as third-class levers; sometimes they are first-class levers. As we open a door by pushing near the hinge, we make it a third-class lever. If we push near the edge, we use it as a second-class lever. (Consider the weight of the door as concentrated at its center of gravity.)

In levers of all classes it may be easily shown that the laws governing them are identical with the principle of moments, if we consider the center of moments as coincident with the fulcrum.

### *C.* THE PULLEY

**167. The Pulley** consists of a wheel, usually grooved, so mounted in a frame or block that it may turn readily upon a fixed axis. The wheel is usually made of metal. The frame may be made of metal or of wood. When two wheels are mounted in the same block, the pulley is said to have two *sheaves*. A pulley may have several sheaves, Fig. 138. When a pulley has two or more sheaves, they generally are mounted on a common axis. Sometimes they are mounted on

FIG. 138.—Pulley, three sheaves. All on same axle.

different axes, as in Fig. 139. For the sake of clearness, we shall use pulleys of the latter type in diagrams, although the first type is more common in practice.

**168. Single Fixed Pulley.** A single fixed pulley is really a lever of the first class. The arms *EF* and *RF*, Fig. 140, are equal, hence the mechanical advantage is one. When 1 lb. pulls downward at *A* through a distance of 1 ft., a resistance of 1 lb. at *B* is raised 1 ft. A single fixed pulley gains neither force nor speed; its purpose is to change the direction in which a force is applied.

FIG. 139. — Pulley, three sheaves.

FIG. 140. — Single fixed pulley.

**169. Single Movable Pulley.** The single movable pulley is really a lever of the second class. In Fig. 141, the effort *E* acts upon the arm *EF*, which is the diameter of the pulley. The resistance *R* acts upon the arm *RF*, which is the radius of the pulley. Since the diameter is twice the radius, the mechanical advantage of the single movable pulley is two. When the effort at *A* moves 2 ft. the resistance at *B* is lifted 1 ft. If we fasten both ends of the cord, it is evident that each point of support bears one half the weight.

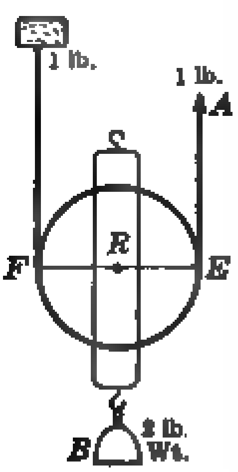


FIG. 141. — Single movable pulley.

**170. Combinations of Pulleys.** Many combinations of fixed and movable pulleys are used. In Fig. 142, one end of the continuous cord or rope is attached to a hook in the movable block; the effort is applied at the other end of the rope. The effort *E* must pull downward through a distance

of 5 ft. to raise the resistance $R$ one ft. There are 5 divisions or strands of cord supporting the movable block. If we use the letter $n$ to represent the number of strands of cord supporting the movable block in any combination of fixed and movable pulleys where the cord is continuous, then $En = R$. *The mechanical advantage equals the number of strands supporting the movable block.*


FIG. 142. — Five strands support the movable block.

If one end of the cord is attached to the fixed block, as in Fig. 143, then the effort moves four times as far as the resistance. The number of strands supporting the movable block is four, which is the mechanical advantage of the system shown.

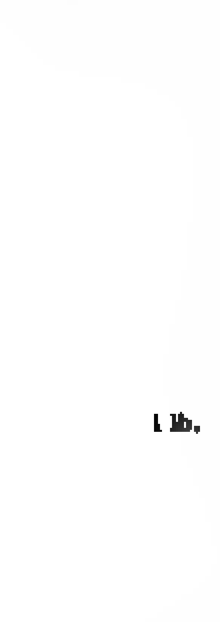



FIG. 143. — Four strands support the movable block.

## *D.* WHEEL AND AXLE

**171. The Wheel and Axle.** This simple machine consists of a wheel or crank rigidly attached to an axle so that both are free to turn about a common center. The effort is applied at some point on the circumference of the wheel and the resistance at some point on the circumference of the axle. While the effort moves a distance equal to the circumference of the wheel, the resistance traverses a distance equal to the circumference of the axle; then

$$\text{M.A.} = \frac{\text{circumference of wheel}}{\text{circumference of axle}}.$$

Since the circumferences of circles have the same ratio as their diameters or radii, then

$$\text{M.A.} = \frac{\text{diameter of wheel}}{\text{diameter of axle}}, \text{ or } \frac{\text{radius of wheel}}{\text{radius of axle}}.$$

From Fig. 144, we see that the wheel and axle is merely a modification of a first-class lever. The effort arm $EF$ equals the radius of the wheel; the resistance arm $RF$ equals the radius of the axle.

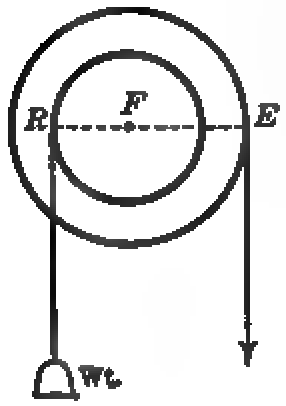



Fig. 144. — Wheel and axle.

**172. Applications of the Wheel and Axle.** The *capstan* used for hoisting the anchor of a ship is an example of the wheel and axle in which the effort is applied at the ends of several levers. See Fig. 145. The *windlass* used for lifting water from wells is another example of the wheel and axle. As the crank of Fig. 146 is turned, the rope is wound upon the axle, thus lifting the bucket and contents. The *hoisting derrick* works on the same principle, and also the *steering wheel* on motor boats.

Fig. 145. — Capstan.

Fig. 146. — Windlass.

## *E.* INCLINED PLANE

**173. The Inclined Plane.** (*a*) *Effort applied parallel to the plane.* Experience teaches us that it is easier to pull a heavy weight up an incline than to lift it vertically. The more gentle the slope of a hill the easier it is to climb to the summit. The effort travels the whole length of the plane in lifting an object a distance equal to the height of the plane, Fig. 147. Therefore, when the effort is applied parallel to the plane,

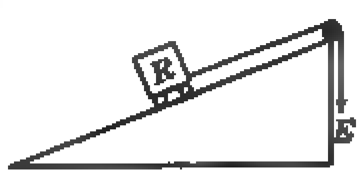



Fig. 147. — Inclined plane.

$$M.A. = \frac{\text{length of plane}}{\text{height of plane}}.$$

Theoretically 1 lb. of effort will pull or push a weight of 5 lb. up an inclined plane 20 ft. long and 4 ft. high.

Effort : resistance = height : length.

(*b*) *Effort applied parallel to the base.* Sometimes the effort cannot be conveniently applied parallel to the plane, but it may be applied parallel to the base or at some angle. A team of horses pulling a log up inclined skids to a wagon walks along the ground, and the pull is parallel to the base of the plane.

When the effort is applied parallel to the base, $M.A. = \frac{\text{base}}{\text{height}}$.

Effort : resistance = height : base.

**174. Grade.** We know that the advantage of the inclined plane becomes greater as the slope is made more gentle. Engineers use the term "grade" to express the ratio of the height of an incline to its length. A hill that rises 5 ft. in 100 ft. of its length has a grade of 5%; if it rises 3 ft. in 100 ft. of its length, its grade is 3%. This is about the maximum grade for a good road, hence in mountain regions the roads often wind about the mountain in a long spiral in order to reduce the grade. A zigzag path, or switch-back, is sometimes used by trolley lines. At one point in the Appalachian Mountains, known as Horseshoe Curve, the Pennsylvania Railroad makes a loop, as it winds its way to a higher level.

## F. THE WEDGE

**175. The Wedge.** The wedge is really a double inclined plane. Since friction plays so important a part in its use, it is difficult to state any accurate law governing its mechanical advantage. Of course the longer the wedge in proportion to its thickness, the easier it is to drive the wedge against

any resistance; hence its mechanical advantage depends upon the ratio of its length to its thickness.

The uses to which the wedge is put vary widely. Farmers use the wedge for splitting rails and posts. Nails, pins, and needles all act as wedges when they are pushed or driven through some resisting object. Cutting tools of nearly all kinds are wedges.

FIG. 148. — Screw.

### G. THE SCREW

**176. The Screw.** If we examine Fig. 149, we see that the screw is merely an inclined plane wound upon a cylinder or axis. The distance between the threads is known as the *interval* or *pitch* of the screw. The effort is generally applied at one end of a lever, the other end being inserted in the head of the screw. See Fig. 148. While the effort describes a complete circle, the screw makes one complete turn, and the resistance moves a distance equal to the pitch of the screw. Then

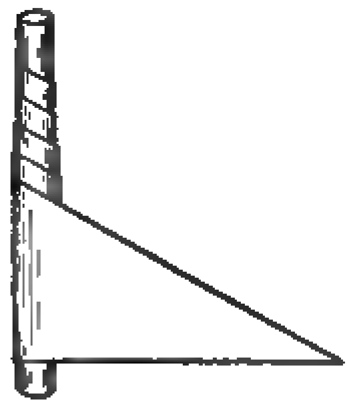


FIG. 149. — The screw is an inclined plane wound on a cylinder.

$$\text{M.A.} = \frac{\text{circumference described by effort}}{\text{pitch}}.$$

Let $r$ equal the length of the lever, and $d$ the pitch of the screw. Then the

$$\text{M.A.} = \frac{2\pi r}{d}.$$

**177. Uses of the Screw.** Bolts, nuts, and screws of all kinds are examples of this simple machine. When the threads on a bolt are cut so that the nut must be turned in

a clockwise direction as it is tightened, the screw is said to be a right-handed one. When the nut must be turned in a counterclockwise direction to tighten it, the screw or thread is said to be left-handed. See Fig. 150. The *letter press* and the *vise* are examples of the screw. The *jack screw* which is used for lifting buildings and other heavy objects is a screw having a very high mechanical advantage. For measuring the thickness of paper and foil, or for finding the diameter of wire, a fine-threaded screw may be used. Fig. 151 shows the *spherometer*. The head of

Fig. 150. — Right and left-handed screws. Square and V-threads.

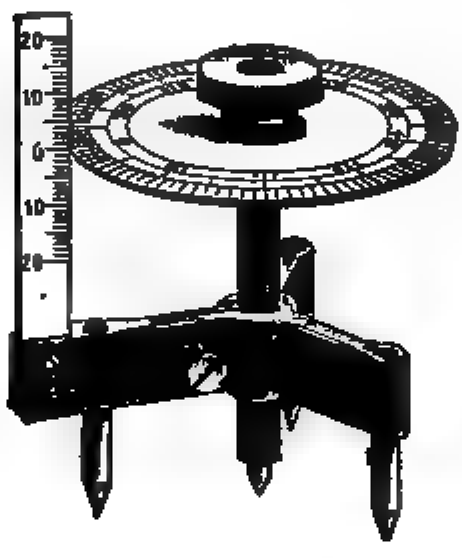


Fig. 151. — Spherometer.

the screw is divided into 50 or 100 parts. If the threads are 1 mm. apart and the head is divided into 100 parts, it is evident that the point of the screw moves only 0.01 mm. when the head is turned from one division to the adjacent one. The *micrometer caliper* of Fig. 152

Fig. 152. — Micrometer.

is used in the same manner. By the use of such a caliper a skilled mechanic can turn a shaft in a lathe to a required diameter within a few thousandths of an inch.

## *H.* COMPOUND MACHINES

**178. Compound Machines.** Many machines are more complicated than the simple machines just discussed. A detailed study of such machines shows that they are usually made up of two or more simple machines acting upon each other. In such cases the mechanical advantage is equal to the product of the advantages of the several simple machines.

Fig. 153 shows a compound lever. The effort *E* acts upon the second-class lever *ED*. If *ED* is 40 in. long and *CD* 8 in., its M.A. is 5. Then 1 lb. at *E* exerts a downward pull of 5 lb. at *C*. But *C* acts downward upon *A*, one end of the first-class lever *AB*. Suppose *AF* is 20 in. long and *BF* 4 in.; this lever has a mechanical advantage of 5, and the 5 lb. acting at *A* will exert an upward force of 25 lb. at *B*. This force of 25 lb. acts on *H*, one end of the second-class lever *OH*, of which the arm *HR* is 28 in. long and *OR* is 4 in. Such a lever has a mechanical advantage of 7. Therefore, 25 lb. at *H* will just counterbalance a weight of 175 lb. applied at *R*. The total advantage of such a system of levers *equals the product* (*not the sum*) *of all the separate mechanical advantages.* For example, $5 \times 5 \times 7 = 175$.

FIG. 153. — Compound lever.

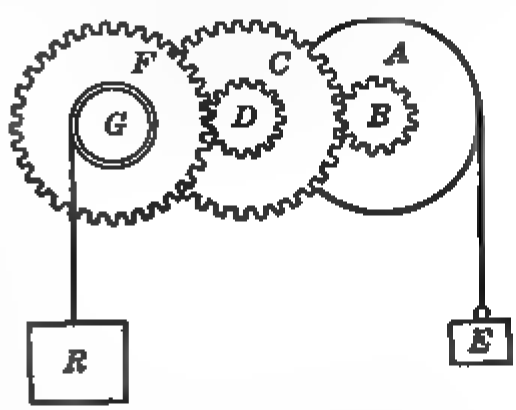



FIG. 154. — Gear wheels. See also Fig. 532.

The *train of gear wheels* of Fig. 154 has a very high mechanical advantage. The wheel $B$ makes one revolution in the same time as wheel $A$, upon which the effort acts. But wheel $C$ makes only that fraction of a revolution which is

equal to $$\frac{\text{number of cogs in } B}{\text{number of cogs in } C}.$$

The same is true of wheel $F$, which revolves only a fraction as rapidly as $D$. The wheels $A$ and $G$ are essentially wheel and axle. The total mechanical advantage of the train of gear wheels equals

$$\frac{\text{radius of } A}{\text{radius of } G} \times \frac{\text{No. of cogs in } C}{\text{No. of cogs in } B} \times \frac{\text{No. of cogs in } F}{\text{No. of cogs in } D}.$$

When the screw $S$ of the *worm wheel*, shown in Fig. 155, is given one complete turn, the wheel $W$ turns through $\frac{1}{n}$ of a revolution, $n$ being the number of cogs in the wheel $W$. Let $l$ equal the length of the crank lever, or the radius of wheel $R$, and $r$ the radius of the axle $A$; then the mechanical advantage of the worm wheel equals $\frac{nl}{r}$.

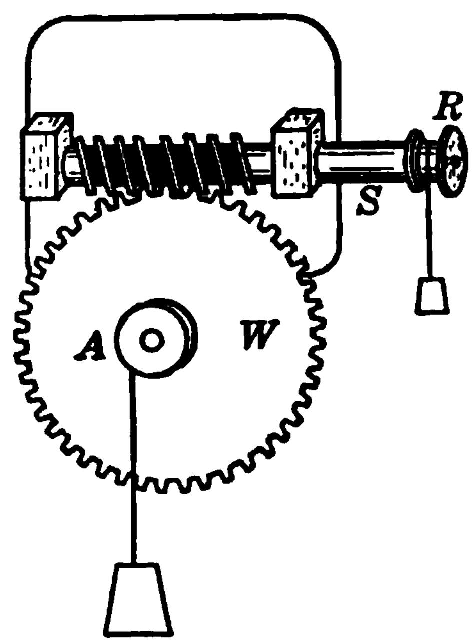


FIG. 155. — Worm gear. See also Fig. 541.

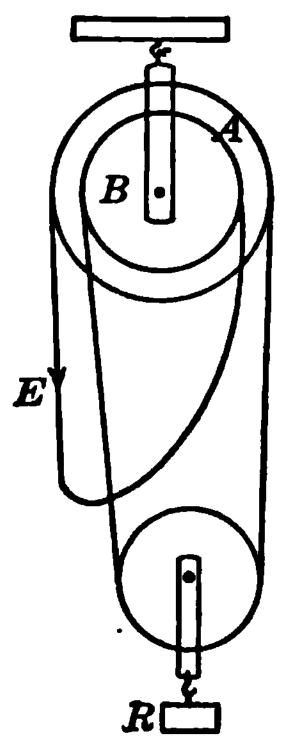


FIG. 156. — Differential pulley. Diagram.

The *differential pulley*, Figs. 156 and 157, consists of two wheels of unequal diameter turning on the same axis, and a movable pulley. An endless chain is used and there are projections on the rim of the wheels into which the links of the chain fit, so that slipping is prevented. While effort $E$ shortens the chain by winding on the wheel $A$ a length of chain equal to its circumference $C$,

a length of chain is unwound from $B$ equal to $c$, the circumference of wheel $B$. The chain is thus shortened by a distance equal to $C-c$, and the resistance $R$, which is attached to the movable pulley, is lifted a distance equal to $\frac{1}{2}(C-c)$, while the effort moves a distance equal to $C$.

$$E : R = \tfrac{1}{2}(C-c) : C. \quad M.A. = \frac{2C}{C-c}.$$

The *steam shovel*, Fig. 158, is a compound machine that one sees everywhere. It is used to excavate for foundations of large buildings, make cuts or fills along railroad beds, dig canals or dredge waterways, scoop up ore, coal, and crushed rock and load them on freight cars, and to strip off the surface layers of earthy materials that are often found covering coal beds or iron ores. The buckets of the very large shovels hold 6 or 8 cu. yd. The student will find it interesting to see how many simple machines he can pick out in the picture of the steam shovel.

Fig. 157. — Commercial type of differential pulley.

**179. How a Lever Is Affected by Its Own Weight.** In our study of the lever we neglected its weight, or assumed that it was weightless. In practice the weight must be considered. Suppose we have a uniform bar 12 ft. long, weighing 24 lb., used as a first-class lever. Suppose we hang a weight of 80 lb. at $B$, 2 ft. from the fulcrum $F$. See Fig. 159. If the lever were without weight, 16 lb. applied at $A$, 10 ft. from the fulcrum, would produce equilibrium, since the mechanical advantage of the lever is 5. But such a weight does not produce equilibrium, since the lever arm $BF$, which weighs 4 lb., tends to produce a clockwise moment about $F$; the lever arm $AF$, which weighs 20 lb., tends to produce a counterclockwise moment. To solve problems

FIG. 158. — The steam shovel scoops up from 1 to 8 cu. yd. of material at a time.

on the lever when the weight is included, we must remember that an object always behaves as if all its weight were concentrated at its center of gravity. Then the weight of the lever given, 24 lb., acting at the center of gravity, $C$, 4 ft. from the fulcrum, produces a counterclockwise moment of $24 \times 4$, or 96. The clockwise moment equals $2 \times 80$ lb., or 160. The difference between the moments, $160 - 96$, is 64. To secure equilibrium, we must have an additional counterclockwise moment of 64. A weight of 6.4 lb. hung at $A$, or a weight of 8 lb. hung 2 ft. from $A$, will produce equilibrium. Where would you place a weight of 40 lb. to produce equilibrium?

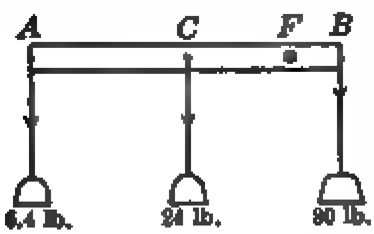


FIG. 159. — Weight of lever produces moment.

**180. Efficiency of Simple Machines.** Since it is impossible to eliminate friction, the efficiency of a machine can never be quite 100%. In the various levers, the efficiency may be nearly 100%. It may seem as if the lever discussed in the preceding paragraph has an efficiency of more than 100%, since 6.4 lb. counterbalance a resistance that theoretically requires 16 lb. In reality, potential energy is being stored in the lever while it is being lifted into position.

The efficiency of a system of fixed and movable pulleys, or the block and tackle, is not nearly so high as that of the lever. The rigidity of the ropes, the friction of the wheels, and the weight of parts lower the efficiency to about 50 or 60% in many cases. The efficiency of the inclined plane may be nearly 90%, if the surface is very

FIG. 160. — The windmill.

smooth. The efficiency of the jack-screw may be as low as 25%.

## *I.* WINDMILL. WATER WHEELS

**181. The Windmill** utilizes the kinetic energy of the wind to perform various kinds of work, especially for pumping water. See Fig. 160. The blades are set in the wheel at such an angle that the force of the wind is resolved into two components, one causing the wheel to rotate rapidly. The vane *V* keeps the plane of the wheel at right angles to the direction from which the wind is blowing.

Fig. 161. — Overshot water wheel.

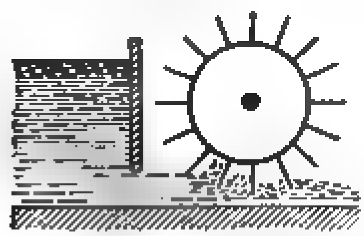


Fig. 162 — Undershot water wheel.

**182. The Overshot Water Wheel**, Fig. 161, uses the potential energy of the water at *R*. The work put into the machine is equal to the weight of the water flowing over the wheel times the distance the water falls. (Same as diameter of wheel.) The efficiency of this type of wheel is often as high as 80%. It is used in mountainous regions where the fall is considerable, but the supply of water is not very great.

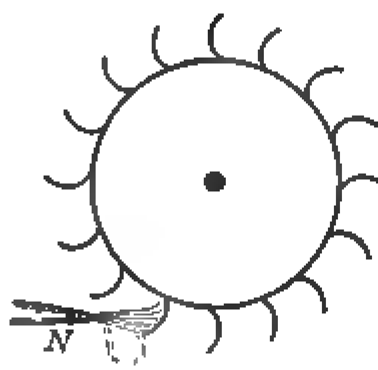



Fig. 163. — Pelton water wheel.

**183. The Undershot Water Wheel**, Fig. 162, utilizes the kinetic energy of flowing water. It is used where the supply of water is abundant and the fall slight. Its effi-

Fig. 164. — Pelton water wheel This wheel is designed for the Big Creek project of the Southern California Edison Company at Los Angeles. It operates under a head of 1860 ft. of water and develops 22,500 H.P. at 375 revolutions per minute.

ciency is usually about 25%. When the water is directed from a nozzle against the blades, an efficiency of 80% is sometimes obtained. The Pelton wheel, Fig. 163, is an example. Fig. 164 shows a large Pelton wheel that is built for installation at Los Angeles, California.

The *water motor*, Fig. 165, works on the same principle as the Pelton wheel. If the pressure of the water from the mains is rather high, a small motor attached to a faucet furnishes sufficient power to operate lathes, grinding wheels, and polishing wheels, or to turn sewing machines.

Fig. 165. — Water motor.

**184. The Water Turbine.** Of the various types of water wheels, the turbine, which was invented in France in 1833, is most extensively used. In one type the wheel, which is mounted on a vertical axis, receives water through several openings from a penstock which is supplied by a turbine pit. See Fig. 166. A set of fixed blades in the case directs the water so that it strikes the blades of the wheel at right angles or nearly so, Fig. 167. The efficiency of the turbine may be as high as 90%.

Fig. 166. — Turbine, showing method of installation.

**185. Transmission of Power.** In a machine shop, we observe that some of the machines are "power" or *driving* machines. On the other hand, such machines as lathes, polishing wheels, planers, saws, and grinding wheels are *driven* machines. Several methods are used for the transmission of power from the *driving* to the *driven* machines. Sometimes the driving shaft is connected with the

Fig. 167. — The fixed blades direct the water against the movable blades.

machine by a train of gear wheels. An endless chain may be used; it passes from one sprocket wheel to another. The bicycle is an example. For short distances belts and pulleys are used for power transmission. Connected as in Fig. 168 *a*, both wheels turn in the same direction. A twisted belt, such as that shown in Fig. 168 *b*, causes the wheels to turn in opposite directions. The ratio of the speeds at which the belt wheels rotate is the same as the ratio of their circumferences. This makes it easy to increase or decrease the speed of a machine by changing the relative diameters of the belt wheels. The gasoline engine of an automobile furnishes power to drive the machine. Before the car can move, the "power" must be transmitted in some way to the rear wheels. Figs. 532 and 533 show how such transmission is usually accomplished by gear wheels of varying diameters. Compressed air and electricity are other methods used for power transmission.

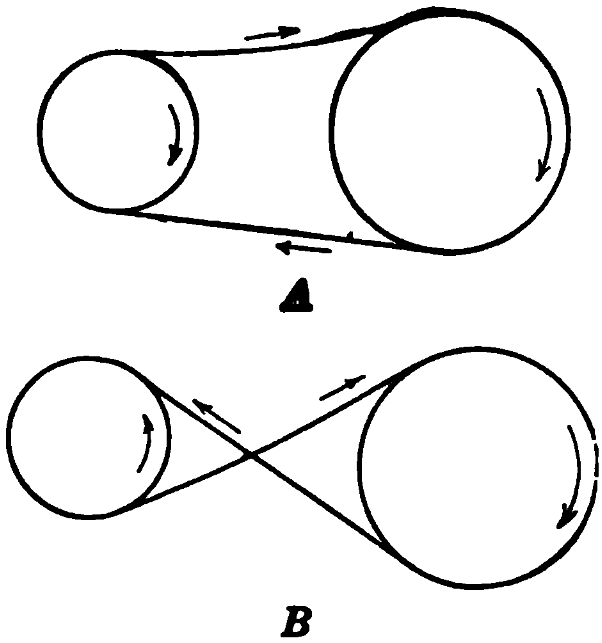



FIG. 168. — Belt transmission. *a*. Both wheels turn in one direction. *b*. Driving and driven wheels turn in opposite directions.

**186. The Cam or Eccentric.** Very often it is desirable to change a rotary motion into a to-and-fro motion, or vice versa. When a sewing machine is operated, the treadle moves up and down, but the band wheel is given a rotary motion. The lower end of the rod that connects the treadle with the band wheel moves up and down, or its motion is *reciprocating*. The upper end is attached to the band wheel at some point a short

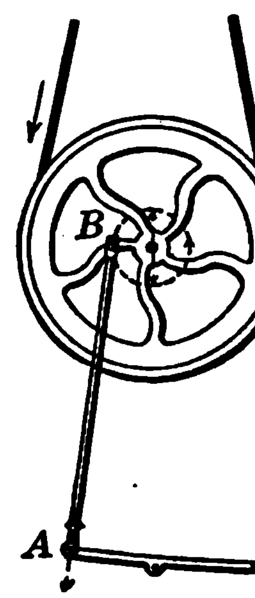



FIG. 169. — Cam, or eccentric, changes to-and-fro motion into a rotary one.

distance from the center (eccentric) upon which the wheel rotates. Fig. 169 shows that while the end of the rod $A$ moves up and down, the other end $B$ describes a small circle whose diameter just equals the translatory motion of $A$. By a belt the power is transmitted to the hand wheel, which in turn controls another eccentric that causes the needle to move up and down. The automatic bobbin winder is another example of the principle of the *cam*, or *eccentric*. The valves of a steam engine and also those of the gas engine are controlled by the cam, or eccentric.

## SUMMARY

A machine is a device used to transform or transfer energy. Theoretically, input equals output. Effort times effort distance equals resistance times resistance distance.

$$\text{M.A.} = \frac{\text{resistance}}{\text{effort}}\text{; it also equals } \frac{\text{distance effort moves}}{\text{distance resistance moves}}.$$

The efficiency of a simple machine equals

$$\frac{\text{useful work accomplished}}{\text{total work expended}}.$$

In all classes of levers the effort : resistance = resistance arm : effort arm.

The mechanical advantage of a block and tackle equals the number of strands supporting the movable block.

In the law of the wheel and axle, $E : R$ = circumference of axle : circumference of wheel. The diameters or radii may be substituted for the circumferences.

When the force is applied parallel to the plane, effort : resistance = height of plane : length of plane. If the force acts parallel to the base, then $E : R$ = height : base.

In the use of the screw, the effort : resistance = the pitch : the circumference described by the effort.

## QUESTIONS AND PROBLEMS

1. Determine the position of the effort, fulcrum, and resistance in each of the following levers: a claw hammer used in pulling nails,

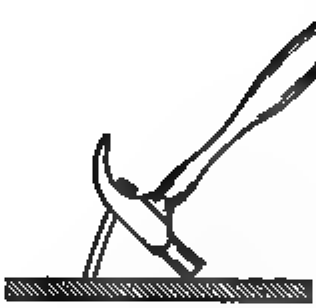


FIG. 170. — Hammer, a bent lever.

Fig. 170; a pinch-bar used for moving a freight car; a pair of sugar tongs; a nut-cracker; the oar of a rowboat.

2. Make a list of ten simple machines used about the household and classify them.

3. Explain how the speedometer shown in Fig. 171 can be used to determine the number of revolutions per minute.

4. What type of machine is a "brace and bit," used for boring a hole in a plank?

5. What type of machine is a screw driver?

6. In what class of lever is the weight of the lever usually a help? In what class is it a hindrance?

7. How heavy a load can a man lift with a single fixed pulley?

8. The turnbuckle of Fig. 172 acts upon one rod which has a right-handed screw; it also acts upon another rod which has a left-handed screw. If each rod has 12 threads to the inch, how much is the space between the ends of the rods increased or decreased by one complete turn of the turnbuckle?

FIG. 171. — Speedometer.

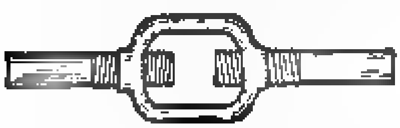


FIG. 172. — Turnbuckle.

9. If a boy can exert a force of 100 lb., how heavy a load can he lift with a second-class lever, 12 ft. long, if the resistance is 3 ft. from the fulcrum?

10. If the lever in the preceding problem is used as a first-class lever, how heavy a load could the boy lift?

11. A boy weighing 60 lb. sits on one end of a teeter board, 5 ft. from the fulcrum. How far from the fulcrum must a 70-lb. boy sit to secure equilibrium?

12. Draw a diagram of a system of fixed and movable pulleys so arranged that 1 lb. of effort will counterpoise 6 lb. of resistance.

**13.** Diagram a block and tackle by which 50 lb. will counterbalance 200 lb.

**14.** In a system of pulleys the effort moves 7 ft. in moving the resistance 1 ft. If 60 lb. are required to lift a load of 300 lb., what is the efficiency of the system?

**15.** Two men operate a windlass. If the wheel has a diameter of 4 ft. and the axle a diameter of 8 in., how much force must each use to overcome a resistance of 2000 lb.?

**16.** How much force must a horse exert to pull a wagon weighing 1000 pounds up a 3% grade?

**17.** A man uses a plank 16 ft. long to roll a barrel weighing 300 lb. to a floor 4 ft. high. If the plank weighs 100 lb., how much work does he do in putting the plank into position? Neglecting friction, how much force must he use to roll the barrel up the plank? If he does 1350 ft. lb. of work in rolling the barrel up the plank, what is the efficiency of the plane?

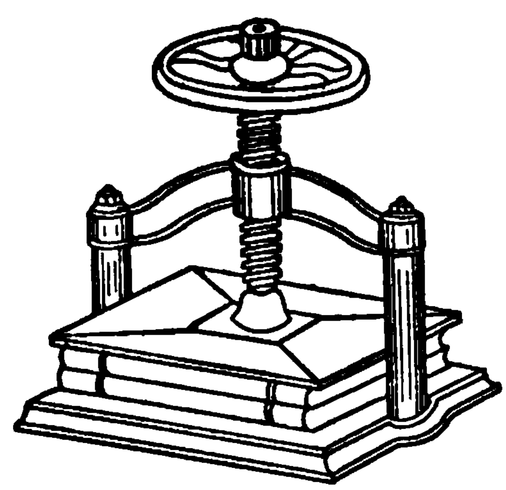


Fig. 173. — Letter press.

**18.** A boy can exert a force of 60 lb. How long a plank must he use to roll a barrel weighing 200 lb. up into a wagon 3 ft. high?

**19.** The threads of a letter press are $\frac{3}{16}$ in. apart. If a force of 40 lb. is applied to the rim of a 12-in. wheel, what is the force of compression? See Fig. 173.

**20.** The threads of a jack-screw are $\frac{3}{8}$ in. apart. The screw is operated by a lever 2 ft. long. If the effort applied is 100 lb., what resistance can be overcome, neglecting friction?

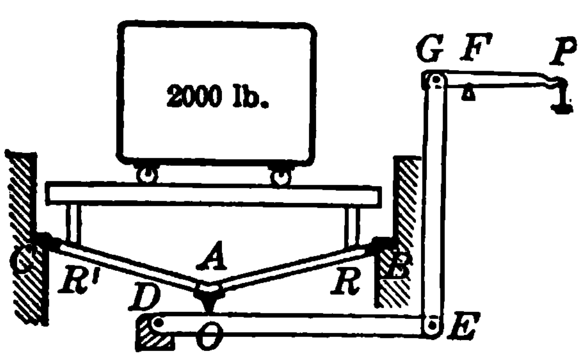



Fig. 174. — Platform scales.

**21.** A jack-screw is operated by a lever 18 in. long. The pitch of the screw is $\frac{1}{4}$ in. If 40 lb. are required to lift a weight of 4500 lb., what is the efficiency of the screw?

**22.** In the hay scales of Fig. 174, the levers $AB$ and $AC$ are each 8 ft. long; $BR$ and $CR'$ are each 8 in. long; $DE$ is 10 ft., and $OD$ is 1 ft.; $GF$ and $PF$ are 9 and 30 in. long respectively. What weight

at $P$ is needed to counterbalance a weight of 2000 lb. on the platform?

**23.** A uniform bar 4 ft. long weighs 16 lb. When a certain weight is applied at $A$, the combination balances on the fulcrum $F$, which is 1 ft. from $A$. Find the value of the weight.

**24.** The diameters of the wheels of a differential pulley are 18 and 16 in. respectively. What is the mechanical advantage? If 100 lb. must be applied to the rim of the larger pulley to lift a weight of 1200 lb., what is the efficiency?

**25.** A ladder used as a scaffold is 12 ft. long and weighs 100 lb. Each end is supported by a block and tackle in which 3 strands support the movable block. If the painter, who weighs 168 lb., stands 1 ft. from one block, with what force must he pull to raise the end of the ladder?

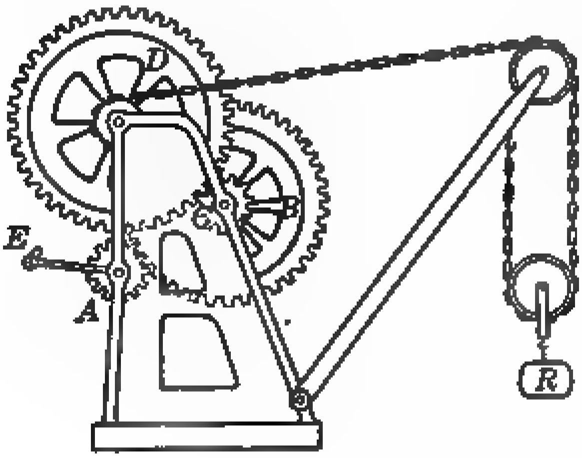



FIG. 175. — Builder's crane.

**26.** The front sprocket wheel of a bicycle has 28 sprockets; the rear wheel has 7. If the bicycle wheel has a diameter of 30 in., how far does the bicycle move forward with one complete turn of the pedals? If the pedal revolves at the rate of 60 times per minute, at what speed per hr. is the bicycle driven?

**27.** The lever of a worm wheel similar to that shown in Fig. 155 is 2 ft. long. The wheel has 90 cogs. If the axle has a diameter of 4 in., what load can be lifted by a force of 10 lb.?

FIG. 176. — Derrick.

**28.** The crane of Fig. 175 has a lever arm of 20 in. The gear wheels $A$, $B$, $C$, and $D$ have 12, 60, 12, and 72 cogs respectively. If the axle has a radius of 4 in., what is the mechanical advantage of the crane?

**29.** Fig. 176 shows a simple derrick. The crank $C$ is 2 ft. long. The axle upon which the rope winds is 4 inches in diameter. There are 60 cogs in $D$ and 10 in $B$. If the end of the rope $R$ is attached to a system of pulleys in which 5 strands support the movable block, what force at $C$ will be required to lift a weight of 12,000 pounds?

*Suggested Topics.* Screw Propellers. Caterpillar Tractors. Headers as Used in Wheat Fields. Stripping.

## CHAPTER 9

# HEAT — THERMOMETRY

**187. Nature of Heat.** Prior to the nineteenth century heat was thought to be a weightless fluid, called *caloric.* When in 1799 Sir Humphrey Davy melted two pieces of ice by rubbing them together, he proved that heat is a form of energy. We have learned that all matter is composed of very small particles called molecules, which are in constant motion. As the velocity of the molecules of a body increases, its temperature rises. The Indians formerly started fires by rubbing two sticks together until the heat produced by friction enkindled them. Boy Scouts now use "fire-sticks" in a similar manner to start fires when camping. Rubbing the hands together increases molecular motion and warms the hands. Conversely, a decrease in molecular velocity causes a fall in temperature. From a consideration of these facts, we may define heat as kinetic energy due to molecular motion.

**188. Sources of Heat.** (*a*) *The sun.* We get heat from many sources, but the heat from the sun is the most important. Directly or indirectly, nearly all the heat we receive can be traced to the sun as its origin. Plants require heat for their growth, and animals are dependent upon plants. Of the total heat which the sun gives off, it is estimated that the earth receives only $\frac{1}{2,000,000,000}$.

(*b*) *Heated interior of earth.* Molten rock issues from volcanoes and boiling water spouts from geysers. Deep

wells and mines also furnish proof that the interior of the earth is still highly heated. The temperature in the Calumet and Hecla copper mine, which is over one mile deep, is so high that even with the use of compressed air for ventilation, it is difficult to keep the temperature low enough so miners can work.

(*c*) *Chemical action* is a very important source of heat. We depend upon the combustion of wood, coal, etc., to keep our houses warm in winter. The oxygen of the air combines with the burning fuel, while both heat and light are evolved. The oxygen which we breathe unites with the food we eat to keep the temperature of the body at about 98.6° F.

(*d*) *Mechanical energy* can be transformed into heat. *Friction*, *impact*, and *compression* are examples of the method by which mechanical energy may be used to produce heat. It is obvious that in all these cases the velocity of the molecules is increased. Rubbing the head of a match on emery paper heats it by friction to its kindling temperature. A bullet fired against a hard steel plate is apt to be melted by the heat due to impact or collision. As we pump up a pneumatic tire, the pump becomes hot. This is due partly to friction, but more largely to the compression of the gas in the cylinder.

**189. Heat and Temperature.** The amount of heat a body has and its temperature are two very different things. A burning match has a much higher temperature than a steam radiator, but it is not so useful for heating a room. A cup of water taken from a tank of boiling water has the same temperature as the water in the tank, but it has less heat. Ten pounds of water at 80° F. will melt more ice than one pound of water at 100° F. Temperature refers to the *intensity* or *degree* of heat. The *heat* of a body is the *sum of all the kinetic energies* of all its molecules. The *temperature* of a body may be defined as *the average kinetic energy* of its molecules.

**190. Sensation and Temperature.** The terms "hot," "cold," and "warm" are used to indicate temperature. Their use is relative, however, and they often mean very little. A room that feels comfortable to a person who has been resting seems very warm to one who has been exercising vigorously. Given three adjoining rooms, "hot," "warm," and "cold" respectively. One person going from the first room to the second finds it "cold," while the same room feels "warm" to another person entering it from the third room. The temperature sense is so unreliable that thermometers are used to measure temperature.

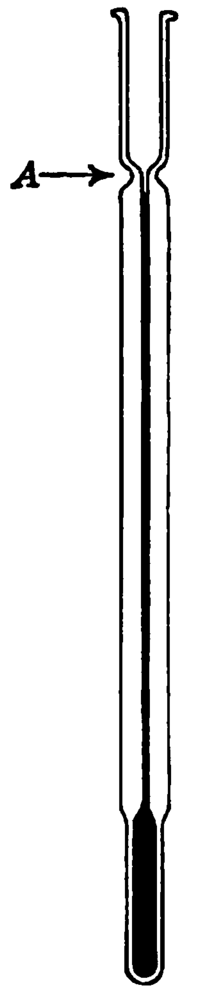


FIG. 177. — Thermometer bulb and stem.

**191. Construction of the Mercury Thermometer.** In constructing a thermometer, a bulb is blown at one end of a thick-walled glass tube of uniform bore, Fig. 177. The bulb and part of the stem are then filled with mercury. When the bulb is heated to a temperature slightly higher than the highest temperature for which the thermometer is to be used, the tube is then sealed at *a*. All the air has been expelled and as the mercury contracts upon cooling, a vacuum is left at the top of the tube. A tube and bulb partially filled in this manner needs only to be graduated to make it a finished thermometer.

**192. Fixed Points.** Since the freezing point and boiling point of water are quite easily determined, they are used as fixed points in graduating thermometers. Since the melting point of ice and the freezing point of water have the same temperature, we generally use melting ice or snow to fix the freezing point on a thermometer. It is more convenient to pack the bulb and stem in melting ice than in freezing water. Therefore the point to which the mercury falls when the bulb and lower part of the thermom-

eter tube are packed in *melting* ice is marked *freezing point*. See Fig. 178.

The thermometer is then suspended in steam from water boiling under a pressure of 76 cm. of mercury, or under a pressure of one atmosphere. The highest point to which the mercury rises is marked *boiling point*, Fig. 179.


Fig. 178. — Freezing point determination.

**193. Centigrade and Fahrenheit Scales.** Several scales are used in graduating thermometers. The Celsius, or Centigrade, scale is used almost exclusively in foreign countries and for *scientific* work in the United States. On the Centigrade thermometer the freezing point is marked *zero* and the boiling point 100. The space between the fixed points is divided into 100 equal parts called *degrees*.

Fig. 179. — Boiling point determination.

On the Fahrenheit thermometer, which is used in the United States for weather observations, the freezing point is marked 32° F., and the boiling point 212° F. The space between the fixed points is then divided into 180 equal parts, or degrees. The difference in temperature between the freezing point and the boiling point of water is 100 Centigrade degrees or 180 Fahrenheit degrees. Therefore 100 Centigrade degrees

C. F

Fig. 180. — C. and F. scales compared.

must equal 180 Fahrenheit degrees, and 1° C. equals 1.8° F. (Fig. 180.).

Suppose we wish to change 20° C. to the corresponding reading on the Fahrenheit scale; we may multiply 20 by 1.8 and add 32°. We must add 32° because the temperature was 20° C., or 36° F., above the freezing point, which is 32° on the Fahrenheit scale. *To change Centigrade readings to Fahrenheit, multiply the Centigrade reading by 1.8, and add 32.* Conversely, *to change Fahrenheit readings to Centigrade, subtract 32 from the Fahrenheit reading and divide by 1.8.*

**194. Limitations of the Mercury Thermometer.** Since mercury freezes at −39° C., it cannot be used to measure temperatures below that point. For lower temperatures alcohol is often used. The freezing point of alcohol is −130.5° C.; it is often colored red or blue and used in thermometers for very cold countries to measure temperatures below the freezing point of mercury. For *very* low temperatures a gas thermometer is used. See Fig. 181. The hydrogen gas with which the bulb is filled contracts upon being cooled and the mercury falls in the tube $C$. The tube $C$ is then lowered until the mercury reaches the former level $B$. The temperature is determined by the *change of pressure* required to keep the volume of hydrogen gas constant (Boyle's law).

Fig. 181. — Gas thermometer.

The boiling point of mercury is 357° C.; therefore the mercury thermometer is not suitable for measuring very high temperatures. A gas thermometer may be used, or electrical instruments such as the platinum resistance thermometer and the pyrometer.

**195. Special Thermometers.** The normal temperature of the human body is 98.6° F., or 37° C. Since the variation in temperature is never more than a few degrees, the *clinical* thermometer used by physicians has only a short scale,

usually graduated from 92° F. to 110° F. The tube is constricted just above the cylindrical bulb. When the mercury expands it is easily forced past this constriction, but as it cools the cohesion between the mercury molecules is not great enough to pull the thread of mercury back past the constriction. Thus the top of the mercury column indicates the highest temperature registered. After the reading has been taken, the thermometer is given a quick jerk to shake the mercury back into the bulb and set it for the next reading. See Fig. 182.

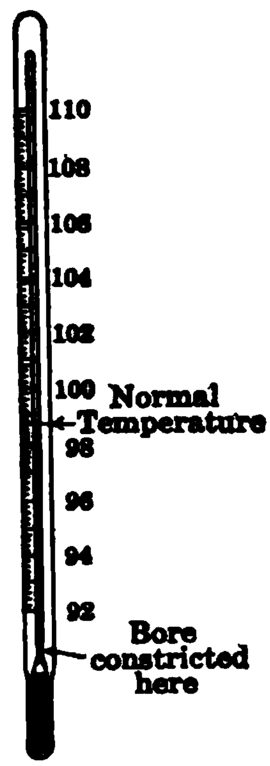



FIG. 182. — Clinical thermometer.

*Maximum and minimum thermometers* are used at Weather Bureau stations to show the highest and lowest temperatures during each day. One type of *maximum* thermometer is constructed just like the clinical thermometer. It is set at a certain hour of the day by shaking the mercury down into the bulb. As the temperature increases the mercury rises in the tube; it will stand in the tube at the highest point reached during the day.

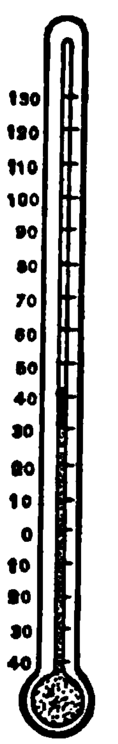


FIG. 183. — Minimum thermometer.

In the *minimum* thermometer the bulb is filled with alcohol. The surface tension of the alcohol drags a small index along the tube as the alcohol cools and contracts. The index is left at the lowest point reached during the time interval, since the alcohol flows past it upon expanding. See Fig. 183.

*Self-registering* thermometers, such as that shown in Fig. 184, are used to keep a continuous record of the temperature. The cylinder, which is turned by clock-work, makes one revolution per week. A pen or pencil carried by the lever arm records the temperature on a sheet of ruled paper which is wound on the cylinder.

FIG. 184. — Thermograph, or self-registering thermometer.

## SUMMARY

The sun, the interior of the earth, chemical action, friction, impact, and compression are the chief sources of heat.

Heat is the sum of the kinetic energies of all the molecules of a body. The temperature of a body is the average kinetic energy of its molecules.

Sensation is an unreliable method of determining temperature. A thermometer is an instrument devised for that purpose.

To change Centigrade readings to Fahrenheit, multiply the reading by 1.8 and add 32; to change Fahrenheit readings to Centigrade, subtract 32 from the Fahrenheit reading and divide by 1.8.

## QUESTIONS AND PROBLEMS

1. Why do sparks sometimes fly from a car wheel when the brakes are applied?

2. Why must a thermometer tube be of uniform bore?

3. Should a thermometer have a spherical or a cylindrical bulb? Give a reason for your answer.

4. Air must be cooled before rain falls. At the tropics the air-currents are descending. How do you account for the arid regions in Australia?

5. How does the size of the bulb of a thermometer affect its sensitiveness? Can you think of another factor that would affect its sensitiveness? Explain.

6. The boiling point of liquid ammonia is $-34°$ C. What is it Fahrenheit?

7. Reduce the following Centigrade readings to Fahrenheit: $-40°$ C.; $20°$ C.; $-273°$ C.; $3000°$ C.; $-190°$ C.; $-10°$ C.

8. Reduce the following Fahrenheit readings to Centigrade: $170°$ F.; $-299°$ F.; $6332°$ F.; $80°$ F.; $-10°$ F.; $10°$ F.

*Suggested Topic.* High and Low Temperature Measurements.

## CHAPTER 10

# HEAT — EXPANSION

**196. Effects of Heat.** In our study of heat, we are especially concerned with the effects which heat produces. (1) We know that the temperature rises when heat is absorbed; (2) heat very often changes the state of matter, as in the melting of ice; (3) heat often causes chemical action, as in the cooking of foods; (4) the size of an object almost always increases when it is heated; and, (5) heat sometimes produces an electric current. One method of measuring temperature consists in measuring the strength of the electric current that is produced when two unlike pieces of metal in close contact with each other are heated.

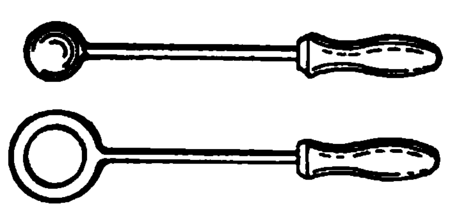


FIG. 185. — Cold ball passes through ring, heated ball cannot.

**197. Expansion of Solids.** With very few exceptions, solids expand when heated. They increase in length, breadth, and thickness. When the ball shown in Fig. 185 is put through the ring and then heated, it cannot be removed until it is again cooled. Cement walks often buckle in hot weather. Telephone wires sag more in summer than in winter. Sometimes wires contract so much in winter that they either break or pull down the poles to which they are fastened. The space between the ends of railroad rails is greater in winter than in summer. Carriage tires are heated before they are put on the wheel and then contract upon cooling, thus making them very tight. Rubber is an exception to the gen-

eral rule of expansion of solids, since it contracts when heated.

**193. Measurement of Expansion.** The expansion of solids is generally so small that the amount cannot be accurately measured, unless some device is used to multiply the increase. Such an apparatus is shown in Fig. 186. One end

FIG. 186. — Cowen's apparatus.

of the metal tube of which we wish to find the increase in length is stationary. The other end rests on a small rod to the end of which a pointer is attached. When steam is passed through the tube, it expands, rolling the rod and turning the pointer through a certain number of degrees. The circular protractor makes it easy to read the number of degrees. The diameter of the rod is easily measured and its circumference computed; the fractional part of the circumference through which it was turned equals the expansion of the tube. It is a matter of simple arithmetic to compute the amount of expansion per unit length when the tube is heated one degree. *The increase per unit length per degree change in temperature is called the coefficient of linear expansion.* The expansion of a solid from 0° C. to 1° C. is not always the same as the expansion per unit degree at some other temperature, but the variation is generally a slight one and it is often negligible. Different solids, however, have decidedly different coefficients of expansion, as the following table shows:

Coefficient of Linear Expansion. (1° Centigrade)

| | | | | | |
|---|---|---|---|---|---|
| Quartz | .0000005 | Iron | .000011 | Silver | .000019 |
| Invar | .0000009 | Steel | .000013 | Tin | .000021 |
| Glass | .000009 | Copper | .000017 | Aluminum | .000023 |
| Platinum | .000009 | Brass | .000019 | Zinc | .000029 |

The coefficient of expansion per degree Fahrenheit equals $\frac{5}{9}$ the value given in this table.

It is important to remember that a solid expands in all directions. If only the length increased, solids would be distorted. A thick glass breaks when put in hot water because the surface expands before the inner part of the glass is heated. Glass does not break when it is heated uniformly.

Problem. An iron rod is 65 cm. long at 0° C. How much will it expand when heated to 80° C.? What will be its length at 80° C.?

*Solution.* From the table we see that 1 cm. of iron expands .000011 cm. when heated 1° C.; 65 cm. will expand 65×.000011 cm., or .000715 cm., when heated 1° C.; the change in temperature is 80 degrees, so the actual increase would be 80×.000715 cm., or .0572 cm. The length of the rod at 80° C. would be 65.0572 cm. (Original length plus expansion.)

**199. Applications.** One end of a bridge is often supported on rollers to allow for contraction and expansion. Two short pieces of platinum wire were formerly used as conductors in making electric bulbs. The coefficient of expansion of platinum is the same as for glass, so that the seal is not broken by unequal expansion. A few years ago an alloy was discovered which serves as well for this purpose as the very expensive metal platinum. A nickel-iron alloy called platinite was first used, but an alloy of these two metals sheathed with copper has proved more satisfactory.

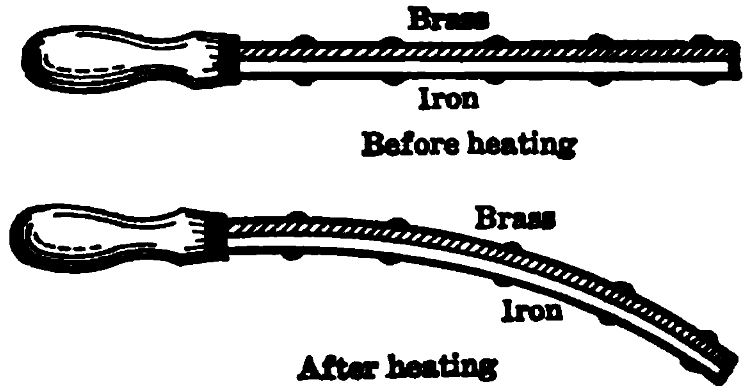



FIG. 187. — Compound bar.

The compound bar of Fig. 187 is made of flat strips of iron and brass, firmly riveted together. Since brass expands more than iron when heated, the combination will curve and the brass will be found on the outside of the curve. Such a bar is used in some *thermostats*. One end is fixed; the other makes or breaks an electrical circuit as the change of temperature causes the bar to become warped. The drafts of the furnace are thus electrically controlled and the room kept at a constant temperature, Fig. 188.

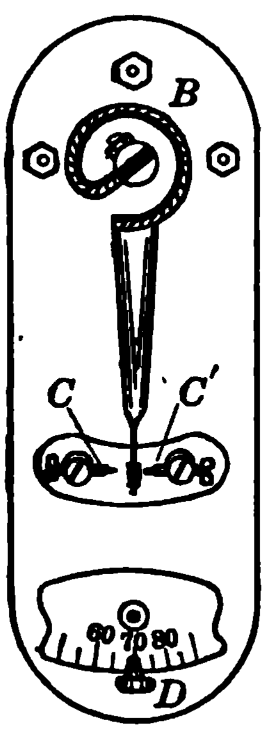



FIG. 188.— Thermostat keeps temperature constant.

A compound bar wound in the form of a spiral is used in metallic thermometers. One end of the bar is fixed at $A$, Fig. 189. The other end $B$ is attached to the pointer which rotates about the axis $C$. The metal on the outside of the curve has the greater expansion.

The *compensated balance wheel* of a watch also has a compound bar. As the radius of the wheel, Fig. 190, grows larger by expansion, it tends to run more slowly; but at the same time the loaded ends $W$ and $W'$ are thrown inward by the bending of the compound bars just far enough so the rate of movement is not affected by any temperature change.

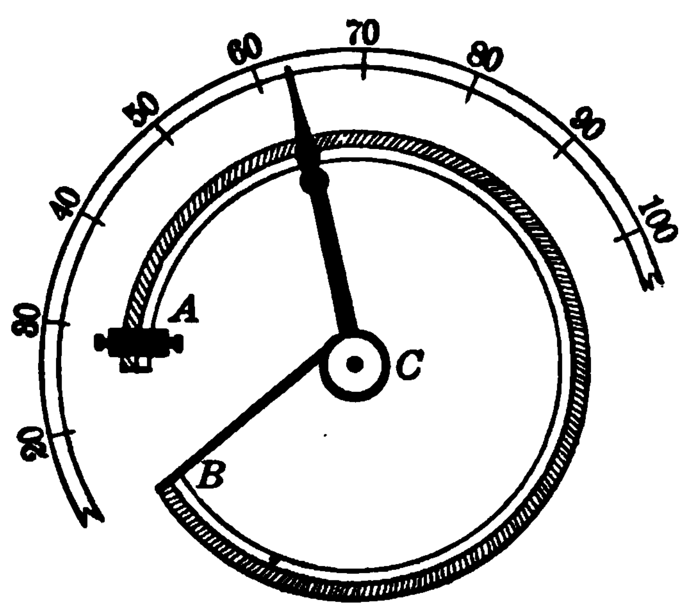



FIG. 189. — Metal thermometer (compound bar).

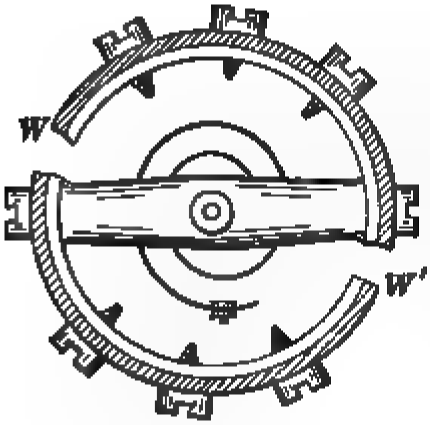



FIG. 190. — Compensated balance wheel.

The pendulum in an ordinary clock vibrates faster in cold weather since the pendulum rod contracts, and a short pendulum vibrates more rapidly than a longer one. Invar is an alloy used in some pendulums because its coefficient of linear expansion is very small. To compensate for temperature changes some clocks have pendulums constructed like those shown in Fig. 191. In (*a*) the center of oscillation is lowered by the expansion of the pendulum rod when heated, but at the same time the expansion of the mercury in the tubes *M* and *M'* raises the center of oscillation by exactly the same amount that it was lowered. A clock with such a pendulum is not affected by temperature changes. In type (*b*) the light rods are of brass and the dark of steel. The brass rods are shorter but have a higher coefficient of expansion than steel. The expansion of the brass rods shortens the pendulum and the expansion of the steel rods lengthens it. The lengths of the rods are so proportioned that the center of oscillation is neither raised nor lowered by temperature changes in such a *compensated* pendulum.

FIG. 191. — Compensated pendulums. *a*. Mercury. *b*. Bars of iron and brass.

**200. Expansion of Liquids.** Fruit-jars and bottles are often filled with hot liquids

and sealed. When the liquid cools it contracts so much that the container is no longer full. We have already learned that alcohol and mercury expand when heated and contract upon cooling. This property of liquids makes them suitable for use in thermometers. An apparatus similar to that shown in Fig. 192 is sometimes used to measure the expansion of liquids. With liquids we generally measure the coefficient of *cubical expansion,* which is approximately *three times the coefficient of linear expansion.*

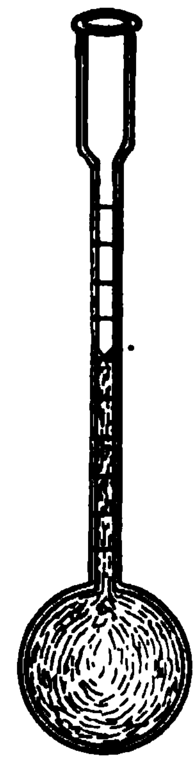


FIG. 192. — Liquid expansion.

Liquids have a higher coefficient of expansion than solids. The amount of expansion also varies considerably at different temperatures. Fortunately, the coefficient of expansion of mercury is practically uniform between 0° C. and 100° C.; otherwise it would be unsuitable for use in thermometers.

The coefficient of cubical expansion of mercury is 0.00018, nearly seven times that of glass; of water, from 5° C. to 8° C., 0.00002; of water, 99° C. to 100° C., 0.00076; of alcohol, 0.0011; and of petroleum, 0.0009.

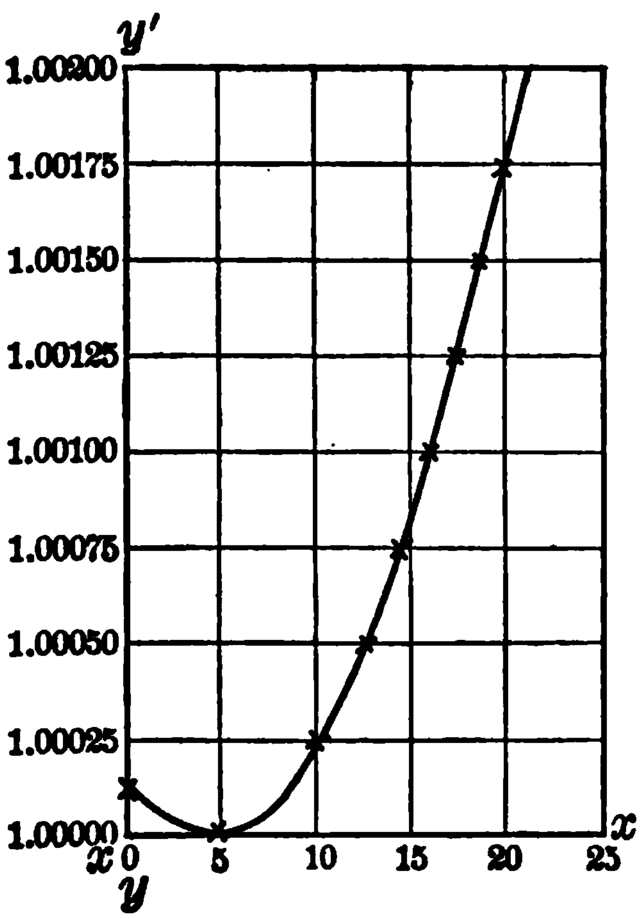



FIG. 193. — Expansion curve of water.

**201. Peculiar Expansion of Water.** When water at 100° C. is cooled, it gradually contracts until a temperature of 4° C. is reached; it then expands as it is cooled from 4° C. to the freezing point. Of course when a substance contracts, its density is increased, since its mass is always con-

stant. Therefore water has its greatest specific weight, 1.00000, at 4° C. At 0° C. its specific weight is 0.9998; at 20° C., its specific weight is 0.99825. We can find the *specific volume* of a body by dividing *one* by its specific weight. In the Metric System the specific volume is that volume of the body in c.c. needed to weigh 1 gm. The peculiar expansion of water is best shown by a curve like that of Fig. 193. In this graph, the specific volumes of water are used as ordinates, and the temperatures as abscissas.

If water continued to contract until the freezing point were reached, the coldest water would sink to the bottom of the container. A pond would then begin to freeze at the bottom instead of at its surface. Lakes and rivers would freeze solid in winter and thaw out only a few feet at the surface in summer. Fish and other aquatic animals would perish. As it is, ice is not formed at the surface until all the water is cooled to 4° Centigrade. The water at the bottom of a frozen pond or lake in winter is 4° Centigrade.

**202. Expansion of Gases.** Like solids and liquids, gases also expand when heated. Unlike solids and liquids, the coefficient of expansion is the same for all gases and it is uniform at all temperatures. The coefficient of cubical expansion, 0.003665 per degree C., is about 20 times that of mercury.

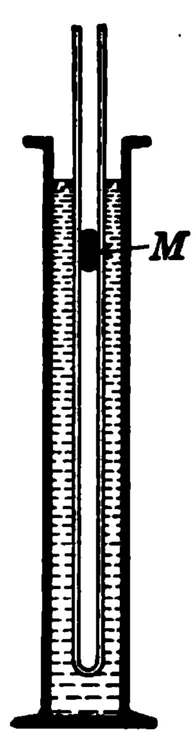


Fig. 194. — Gas expansion.

From experiments conducted in 1787, Charles, a Frenchman, learned that all gases expand the same amount when heated one degree, if the pressure is kept constant. Let us take a small glass tube, sealed at one end, and measure the air column inclosed by the globule of mercury *M*, Fig. 194, when the tube is immersed in ice water. Next let us measure the air column when the tube is immersed in steam. We find that the air column has increased in length $\frac{100}{273}$ of its original length. For each degree of temperature change,

the expansion is $\frac{1}{273}$. If we use other gases, the result will be the same. While Charles was the first to study the expansion of gases, the law sometimes bears the name of Gay-Lussac, who was the first to announce the law governing the relation of the volumes of gases to their temperatures.

**203. Absolute Temperature.** When a gas is cooled below 0° C., it continues to contract, losing $\frac{1}{273}$ of its volume per degree Centigrade. At −100° C., its volume is decreased by $\frac{100}{273}$. Theoretically, a gas cooled to −273° C. would lose $\frac{273}{273}$ of its volume. At zero volume molecular motion would cease and the body would be without heat, or absolutely cold. For this reason, −273° C. is considered zero on the absolute temperature scale. In reality all gases liquefy before absolute zero is reached. Kamerlingh Onnes succeeded in getting the extremely low temperature of −271.3° C., by evaporating liquid helium. The relation between the absolute scale and the Centigrade scale is shown in the following table:

| C. | A. | V. |
|---|---|---|
| 100° | 373° | 373 c.c. |
| 50° | 323° | 323 c.c. |
| 0° | 273° | 273 c.c. |
| −100° | 173° | 173 c.c. |
| −273° | 0° | 0 c.c. |

The column headed *V* shows the changes in volume of a body of gas that measures 273 c.c. at standard temperature, 0° C. From a study of these scales, it is apparent that the law of Charles may be stated as follows: *If the pressure be constant, the volume of a given mass of dry gas is directly proportional to the absolute temperature.* The absolute temperature equals Centigrade temperature plus 273 degrees.

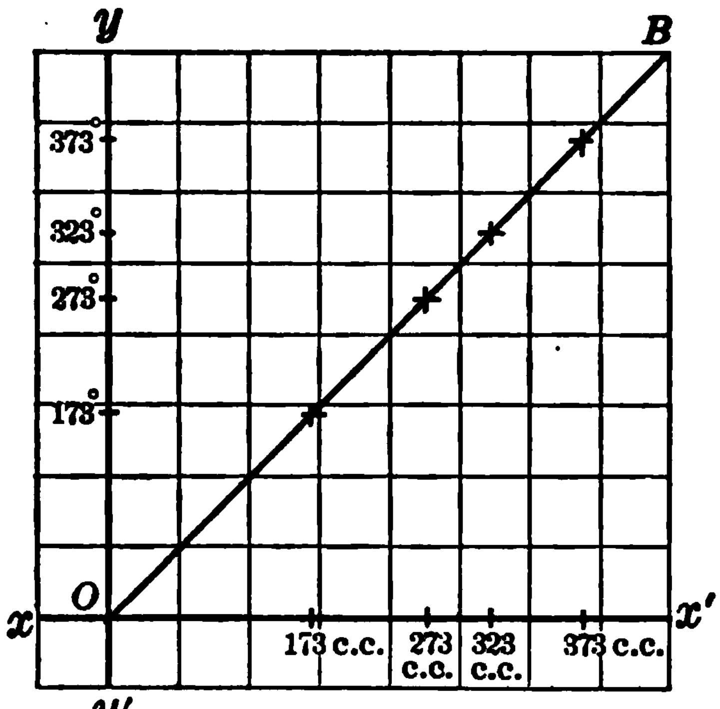



FIG. 195. — Curve to represent law of Charles.

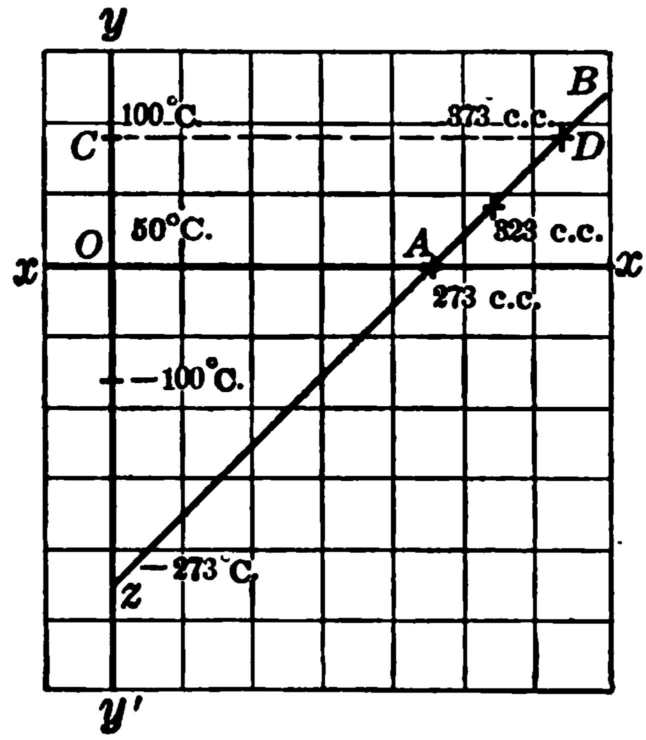



FIG. 196. — Curve to show absolute zero.

Suppose we plot a curve, using the absolute temperatures of the above table as ordinates and the volumes as abscissas. The graph, Fig. 195, is a simple direct-proportion curve, showing that the volume is directly proportional to the absolute temperature.

If we use the Centigrade temperatures instead of the absolute, we then get the curve of Fig. 196. By producing the curve $AB$ downward we find that it intersects the $YY'$ axis at $Z$, a point corresponding to $-273°$ C.; at this temperature the volume is zero. In the similar triangles $ZCD$ and $ZOA$, we observe that $OZ : CZ = OA : CD$. Therefore $OA$ and $CD$, the corresponding volumes, are proportional to $OZ$ and $CZ$, the *absolute* temperatures. They are *not* proportional to the *Centigrade* temperatures.

**204. Problems Involving the Use of the Law of Charles.** Given 400 c.c. of gas measured at 10° C.; suppose we wish to find what volume the gas will occupy at 60° C. We must first reduce the Centigrade temperatures to absolute. 10° C. = 283° A., and 60° C. = 333° A. Let $V$ represent the original volume; $V'$, the new volume; $T$, the original temperature, and $T'$, the new temperature.

Then by the law of Charles, $V:V' = T:T'$.

Substituting, $400 : x = 283 : 333$.

Whence, $x = 470.6$ c.c.

It is quite as simple to solve by fractions. The temperature has increased and the volume will be correspondingly increased. Hence the new volume is $\frac{333}{283}$ of the original volume. $\frac{333}{283} \times 400 = 470.6$ c.c.

Sometimes both the temperature and the pressure change; then it is necessary to solve the problems by the use of the laws of Charles and Boyle.

PROBLEM. Given 500 c.c. of gas at 20° C. and 750 mm. pressure; find what volume the gas will occupy at 30° C. and 760 mm. pressure.

*Solution.* 20° C. = 293° A.; 30° C. = 303° A.

Then, $500 \times \frac{303}{293}$ = the volume corrected for temperature change only.

And, $500 \times \frac{750}{760}$ = the volume corrected for pressure change only.

Since both the temperature change and the pressure change occur simultaneously, we may combine the equations as follows:

$$500 \times \frac{303}{293} \times \frac{750}{760} = \text{corrected volume.}$$

NOTE. The increase in temperature from 20° C. to 30° C. causes the gas to expand by $\frac{303}{293}$ of its volume, and the increase in pressure reduces the volume by $\frac{750}{760}$.

The following formula may be used for solving problems when both the temperature and pressure change: $\frac{PV}{T} = \frac{P'V'}{T'}$. In this formula, $P$, $V$, and $T$ represent the original pressure, volume, and temperature respectively; $P'$, $V'$, and $T'$ represent the new pressure, volume, and temperature.

**205. Force of Expansion.** The force of expansion or contraction is enormous. Broken wires in winter, cracks in pavements, and the bursting of tires when highly heated all testify to the great force exerted by a change in temperature. The magnitude of this force seems to be limited only by the breaking strength of the material at the given temperature. With a steel bar of 1 sq. in. cross-sectional area, the force may be nearly 70 tons.

## SUMMARY

In general solids expand when heated and contract when cooled. The increase per unit length per unit degree is called the coefficient of linear expansion. The increase in volume, or the coefficient of cubical expansion, is three times the linear coefficient.

Liquids have a much higher coefficient of expansion than solids; alcohol expands nearly 30 times as much as steel, and mercury nearly 5 times as much. Water has its maximum density at 4° C.; heated above this temperature or cooled below it, water expands.

The coefficient of expansion of all gases is the same, 0.003665 per degree Centigrade.

## QUESTIONS AND PROBLEMS

1. How would thermometer readings be affected if mercury and glass had the same coefficient of expansion?

2. When two tumblers stick together they may usually be loosened by pouring cold water into the inner one, or by letting hot water run over the outer one. Explain.

3. Why is all the water in a pond cooled to 4° C. before any of it freezes?

4. Fused silica has a coefficient of expansion of about 0.0000005. Give two reasons why it is superior to glass for laboratory apparatus that is to be heated to high temperatures.

5. Laboratory glassware in which liquids are to be heated is made of very thin glass. Explain.

6. Is a football tighter on a cold day or a warm one? Give a reason.

7. An iron steam pipe is 30 ft. long at 20° C. What will be its length when steam is passing through it?

8. The steel cables of the Brooklyn bridge are 5280 ft. long when the temperature is −20° C. What will be their length at 35° C.?

9. A wire is 100 cm. long at 20° C. At 80° C., it is 100.1104 cm. long. What is its coefficient of expansion?

10. A room is heated from 0° to 20° C. What fractional part of the air escapes? If the density of the air at 0° C. was 0.00128 gm. per c.c., what will its density be at 20° C.?

**11.** A man buys 100 gallons of alcohol when the temperature is 0° C. How many gallons will there be when the temperature rises to 20° C.?

**12.** Given 900 c.c. of gas measured at 18° C. and 745 mm. pressure. Find what volume it will occupy when measured at 25° C. and 770 mm. pressure.

**13.** Steel rails which are laid when the temperature is 20° C. measure 34 ft. If the maximum temperature is 110° F., how much space should be left between the rails?

**14.** Why are rivets and iron bolts heated red-hot before they are put in bridges and steel plates?

**15.** A gas measures 400 c.c. at a temperature of 25° C. and a pressure of 800 mm. To what temperature must the gas be cooled if its volume is reduced to 350 c.c. when the pressure is 760 mm.?

**16.** Explain how the baking of bread is an application of the law of Charles.

**17.** Why is invar used in making the measuring tapes used by surveyors?

**18.** Pyrex glass is rich in silica. Explain its use for baking dishes and for laboratory apparatus.

**19.** Would you expect to find high or low temperatures associated with high barometer areas? Explain.

*Suggested Topics.* Work of Charles, Gay-Lussac, and Kamerlingh Onnes.

## CHAPTER 11

# HEAT UNITS — CHANGE OF STATE

**206. Heat Units.** We have learned that thermometers are used to measure temperature. We know, too, that two substances may have the same temperature, but different quantities of heat. When a man buys coal he is interested to know how much *heat* he has bought, not how high a temperature the coal will produce. In the laboratory it is possible to measure the quantity of heat a sample of coal will furnish in terms of the *effect* it can produce. One of the *heat units* used is the *calorie.* It may be defined as the *quantity of heat required to raise the temperature of 1 gram of water 1° C.* When one gram of water cools through one Centigrade degree, it loses 1 calorie of heat. One gram of good soft coal gives out about 8000 calories of heat during combustion. In dietetics the *large Calorie* is used; it equals 1000 small calories. When we say " A thick slice of bread furnishes 100 Calories," we mean that the bread, if totally oxidized, would supply the body with enough heat to raise the temperature of one kilogram (1000 gm.) of water 100° C. Engineers often use the *British Thermal Unit* (*B.T.U.*), *which is the amount of heat required to raise the temperature of 1 lb. of water 1° F.* One B.T.U. equals 252 calories. One pound of coal has a heat value of from 10,000 to 16,000 B.T.U.

**207. Heat Capacity.** Substances vary greatly in their capacity for absorbing heat. This fact may be clearly shown by an experiment devised by Tyndall. Given five balls, aluminum, iron, copper, zinc, and lead, all of the same weight.

Let us heat them all to the same temperature, say about 150° C., and put them on a thin paraffin plate. See Fig. 197. The aluminum melts its way through the paraffin block most rapidly, followed by the iron. The copper and zinc then follow at about the same rate, while the lead melts the paraffin very slowly. The rate of melting in each case depends upon the heat capacity of the metal. *The thermal capacity of a body may be defined as the amount of heat required to raise its temperature 1° C.* The heat is absorbed by a body as its temperature rises, and given off again upon cooling. The aluminum in the experiment absorbed more heat and then gave off more heat to the paraffin than any of the other metals. Water has a very high heat capacity, hence it heats slowly and cools slowly.

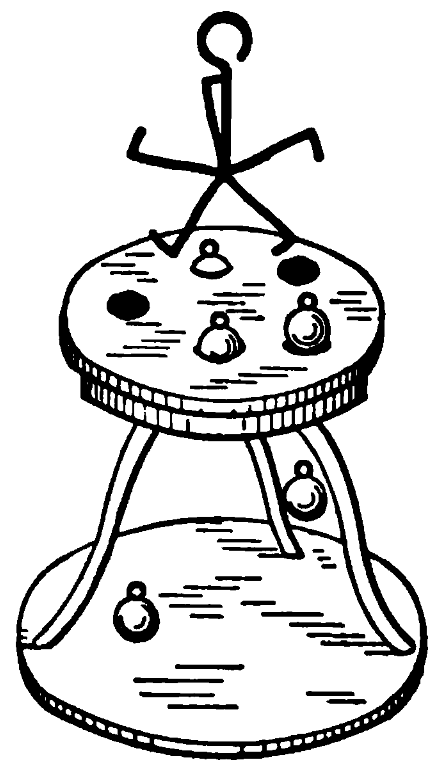


FIG. 197. — Heat capacity varies.

**208. Specific Heat.** The specific heat of a body may be defined as the ratio of its heat capacity to that of water. The specific heat of water is unity, as may be seen from the definition of the calorie. Therefore, the *specific heat of a substance is the number of calories required to raise the temperature of one gram of that substance 1° C.*, or in the English System it is the number of B.T.U.'s required to raise the temperature of 1 lb. of water 1° F. From the table of heat constants in the appendix, it may be seen that the specific heat of most substances is very low compared to that of water. For example, iron is only 0.113, about $\frac{1}{9}$ as great. This means that a certain weight of iron when heated rises in temperature about 9 times as fast as the same weight of water, and it cools about 9 times as rapidly. Numerically, 1 calorie raises the temperature of 1 gm. of water 1° C.; 100 calories raise the temperature of 1 gm. of water 100° C.; and

1000 calories would raise the temperature of 10 gm. of water 100° C. In comparison, only 113 calories would be required to raise the temperature of 10 gm. of iron 100° C. In all cases, if the substance does not change its state, *its weight in grams times its change in temperature in Centigrade degrees times its specific heat equals calories;* or, *weight in pounds times change in temperature in degrees Fahrenheit times specific heat equals British Thermal Units.*

**209. Prevost's Theory.** If we touch a hot metal pan, the hand gains heat; if we touch an object cooler than the hand, heat flows from the hand to the object. When two substances of unequal temperature are brought into contact, or are mixed, the warmer always loses heat and the cooler gains heat until both have the same temperature. *Prevost showed that the total number of heat units lost by the warmer substance equals the number of heat units gained by the cooler substance.* This statement, commonly known as the *law of heat exchange,* forms a basis for working problems involving the transfer or exchange of heat.

**210. Method of Finding Specific Heat.** Specific heat is usually determined by the method of mixtures. Suppose we wish to find the specific heat of brass. A calorimeter, or metal cup, whose specific heat is known is weighed. It is filled about $\frac{2}{3}$ full of water and again weighed. The difference is the weight of water used. A lump of brass is weighed and suspended in steam from boiling water until its temperature is 100° C. The temperature of the water in the calorimeter, which should be slightly below room temperature, is accurately measured and the brass then quickly introduced. The water is stirred with the thermometer until the mercury stops rising, and the final temperature is then read. Suppose we obtain the following data:

| | |
|---|---|
| Weight of calorimeter . . . . . . . . . | 110 gm. |
| Specific heat of calorimeter . . . . . . | 0.09 |
| Weight of water . . . . . . . . . . . | 405 gm. |

| | |
|---|---|
| Weight of brass . . . . . . . . . . . . | 201.9 gm. |
| Initial temperature of the water . . . . . | 20° C. |
| Initial temperature of brass . . . . . . | 100° C. |
| Final temperature of water and brass . . . | 23.5° C. |

The brass loses heat as follows:

Weight (gm.) $\times$ change of temperature $\times$ specific heat = calories.

Or, $201.9 \times (100-23.5) \times X$ = calories.

The water and the calorimeter gain heat as follows:

$110 \times (23.5-20) \times 0.09 = 34.65$ calories, gained by calorimeter.

$405 \times (23.5-20) \times 1.00 = 1417.5$ calories, gained by water.

Total calories gained = 1452.2.

By Prevost's theory, *heat lost equals heat gained.*

Then, $201.9(76.5)\,X = 1452.2$ calories.

Whence, $X = 0.094$, the specific heat of brass.

This method is a general one. In all problems involving heat exchange and specific heat, the student needs to consider *which substances lose heat and which gain heat;* he should bear in mind the fact *that calories gained equal calories lost;* and he must remember *that weight in grams times change in temperature in degrees Centigrade times specific heat equals calories.*

**211. Effects Produced by High Specific Heat of Water.** Because water has a high specific heat, it takes a long time to heat a quart of water to the boiling point. The same property, however, makes it very useful for the hot water bottle in the sick room, since water cools very slowly. An island has a more equable climate than the interior of a continent. In early summer the surrounding water does not heat so quickly as the land, but it does not cool so quickly in late autumn. Cities situated on large bodies of water are not subject to so great extremes of temperature, nor to such sudden changes of temperature as inland cities.

**212. Fusion.** *Fusion, melting, or liquefaction is the process of changing from a solid to a liquid state.* The temperature at which such change occurs is called the *melting point.* The temperature at which a crystalline solid melts

and the temperature at which solidification or freezing occurs are usually the same. Pure substances generally have a definite melting point. In fact the determination of the melting point is often used as a test for purity, since the presence of a small amount of impurity often changes the melting point decidedly.

Substances like glass and sealing wax have no definite melting point, but they soften gradually when heated. Such substances may be heated and then bent, molded, or welded. Wrought iron becomes plastic when it is heated. The blacksmith heats two pieces of wrought iron until they begin to soften, and then pounds them together into one piece. Cast iron has a sharp melting point, hence it cannot be welded. The tensile strength of a substance is reduced as its temperature rises. Structural material, such as steel, frequently collapses during fires as a result of such weakening, even before the melting point is reached.

**213. Change of Volume on Solidification.** If we pour molten paraffin into a tumbler and let it solidify, the center will be much depressed, showing that paraffin contracts during solidification. Most metals and alloys behave in the same manner.

When water solidifies, the reverse is true. Water pitchers are often broken by the expansion of water as it freezes. A pan half full of water shows a bulging, convex surface when the water freezes. The force of expansion is enormous; rocks are often broken by water collecting in crevices and expanding when it freezes. Water pipes often burst when the water freezes. The volume occupied by the ice is about 1.1 times that of the water from which it was formed. Bismuth and antimony also expand upon solidification. Antimony is a constituent of type-metal; since it expands in the mold, it makes the type clear-cut.

**214. Why Change of Volume When Water Freezes Is Important.** If water continued to contract when cooled

below 4° C. and did not expand upon freezing, the density of ice would be greater than that of water. The first layer of ice formed would sink. Each successive layer would also sink as soon as formed until the entire body of water would be frozen solid. Since the sun's rays do not penetrate water readily, only a few feet of the surface ice would be melted during the summer. The Great Lakes, as well as other lakes and rivers in the same latitudes, would be closed to navigation.

**215. Effect of Pressure on the Melting Point.** The melting points of solids that contract on solidifying are raised by an increase of pressure. The converse is true of solids that expand on solidifying. A very great pressure is required, however, to change the melting point decidedly; a pressure of one atmosphere lowers the melting point of ice only 0.0075° C. If snow is not much colder than the melting point, it "packs" readily. In making a snowball some of the snow at the surface melts under pressure and freezes again as the pressure is reduced. Suppose we suspend two weights by a wire over a block of ice, as in Fig. 198. The pressure causes the ice to melt under the wire, which gradually cuts its way through the block. As the pressure decreases after the wire has passed, the water freezes again. *Melting under pressure and subsequent freezing when the pressure is released is called regelation.* It plays an important part in the movement of valley glaciers.

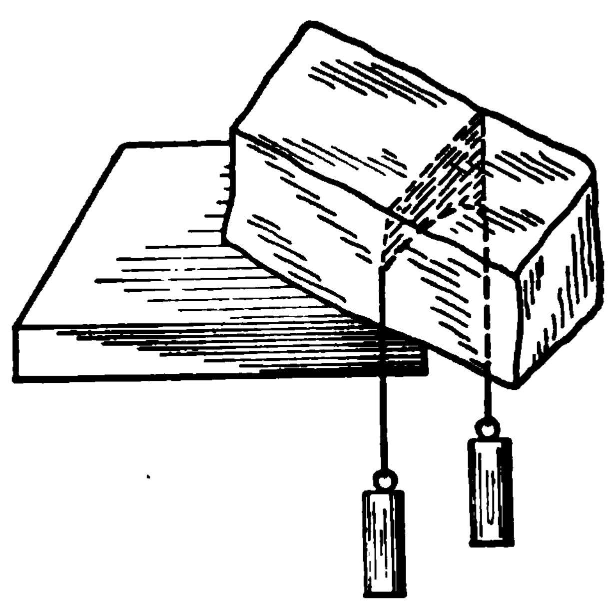


FIG. 198. — Pressure lowers melting point.

**216. Heat of Fusion.** If a pan of ice water containing a few lumps of ice is constantly stirred with a thermometer while it is being heated, the temperature of the mixture

will not rise above 0° C. until all the ice is melted. Heat is certainly being absorbed, but since the temperature does not increase, it is evident that the heat is used only in *melting* the ice. *The number of calories required to melt one gram of a substance without increasing its temperature is called its heat of fusion.* Since the thermometer does not show any evidence of heat transfer, heat of fusion is sometimes called *latent* (hidden) heat. Careful experiments show that it requires 80 calories of heat to convert 1 gm. of ice at 0° C. into water at 0° C.; it requires 144 B.T.U. to change one pound of ice at 32° F. into water at 32° F. Due to its very high heat of fusion, ice makes an excellent refrigerating agent. In melting, ice takes heat from the surrounding substances, thus lowering their temperature.

**217. Determination of Heat of Fusion.** The method of mixtures is used for finding the number of calories needed to melt one gram of a substance. The following data are needed: weight of calorimeter; weight of substance; weight of water used; initial temperature of water; and its temperature when the substance is entirely melted.

PROBLEM. A calorimeter weighing 100 gm. has a sp. ht. of 0.09; it contains 400 gm. of water at 40° C.; 91 gm. of dry ice are introduced. When the ice is all melted the temperature is 18.2° C. What is the heat of fusion of the ice?

*Solution.* Both calorimeter and water lose heat as follows:

$100 \times (40-18.2) \times 0.09 = 196.2$ calories (lost by calorimeter).
$400 \times (40-18.2) \times 1.00 = 8720$ calories (lost by water).
Total calories lost $= 8916.2$

These 8916.2 calories did two things: first, they melted 91 gm. of ice; second, they raised the 91 gm. of water thus formed from 0° C. to 18.2° C.

$91 \times (18.2-0) \times 1.00 = 1656.2$ calories gained by water.
$8916.2 - 1656.2 = 7260$ calories, which were used to melt the ice.
$7260 \div 91 = 79.8$ calories used to melt one gram of ice, or its heat of fusion.

**218. Heat Set Free When Water Freezes.** It is reasonable to expect that heat will be liberated when water freezes. Since energy is indestructible, 80 calories of heat must be liberated for every gram of water at 0° C. that is changed to ice at 0° C. Tubs of water in cellars may give off enough heat on freezing to protect canned fruits and vegetables from freezing. The air is warmed in winter by the heat set free during the formation of snow and ice. For this reason the weather often moderates just before or during a snowstorm.

**219. Heat Absorbed in Solution.** Dissolving salt in water lowers the temperature. A still more decided lowering of the temperature occurs when sal ammoniac, potassium iodide, or ammonium sulphocyanide is dissolved. Some of the heat energy of the solvent is used in dissolving the solute. Because heat energy breaks down the solid, heating the solvent not only causes a substance to dissolve more rapidly, but in almost all cases it increases the total quantity that can be dissolved.

**220. Freezing Mixtures.** In making ice-cream or frozen puddings, ice is not used alone, since its melting point is approximately the same as that of the substance to be frozen. When salt is put on ice, it dissolves in the surface moisture. A saturated solution of salt freezes at −22° C.; therefore the ice melts rapidly when the salt is applied. Both the dissolving of the salt and the melting of the ice absorb heat; the cream or pudding is soon frozen, since the continual removal of heat cools it below its freezing point.

**221. Vaporization.** The process of converting a substance into a gas or vapor is known as *vaporization.* If the process occurs at the surface only, we call it *evaporation.* When we put a basin of water over a gas flame, bubbles of vapor soon form at the bottom of the vessel. As these bubbles rise through the cooler layers of liquid

above they collapse, causing the familiar "singing" so often noticed before liquids begin to boil. When the entire liquid is hot enough so that these bubbles reach the surface freely, evaporation takes place throughout the liquid with visible disturbance; the process is called *boiling* or *ebullition.*

**222. Laws of Evaporation.** *The rate of evaporation increases with an increase of temperature,* since heat increases molecular velocity.

*The rate of evaporation increases as the surface area of the liquid increases.* Liquids evaporate faster from a broad, shallow pan than from a deep, narrow vessel.

*The rate of evaporation increases when the atmospheric pressure is reduced.* Evaporation is very rapid in a vacuum. The molecules escape freely from the liquid surface, since there are no air molecules to hinder their progress.

*The rate of evaporation increases with the rate of change of the air in contact with the liquid.* Wet clothes dry very rapidly on a windy day. The saturated air in the immediate vicinity is removed by the wind and replaced by unsaturated air.

*The rate of evaporation increases as the relative humidity is reduced.* When the air is nearly saturated with vapor, water evaporates slowly.

*The rate of evaporation varies with the nature of the liquid.* Alcohol evaporates much faster than water; ether evaporates faster than alcohol.

**223. Sublimation.** Sometimes solids change directly to vapor without passing through the liquid state. The process is called *sublimation.* By this process such substances as iodine and camphor gum may be separated from impurities. The fact that snow and ice slowly disappear even when the temperature is below the melting point proves that these solids sublime. At 0° C. ice exerts a vapor pressure of 4.5 mm. of mercury.

**224. How Pressure Affects the Boiling Point.** Let us examine the curve shown in Fig. 199. We note that the pressure which water vapor exerts increases very rapidly with the temperature. *A liquid cannot boil until its vapor pressure equals the atmospheric pressure.* At 0° C., water exerts a pressure of 4.5 mm.; at 20° C., its pressure is 17.3 mm.; at 80° C., it has risen to 354.7 mm.; at 100° C., its pressure is 760 mm., or one atmosphere. For this reason, we call 100° C., the *boiling point* of water. If the barometric pressure falls to 733 mm., water boils at 99° C.

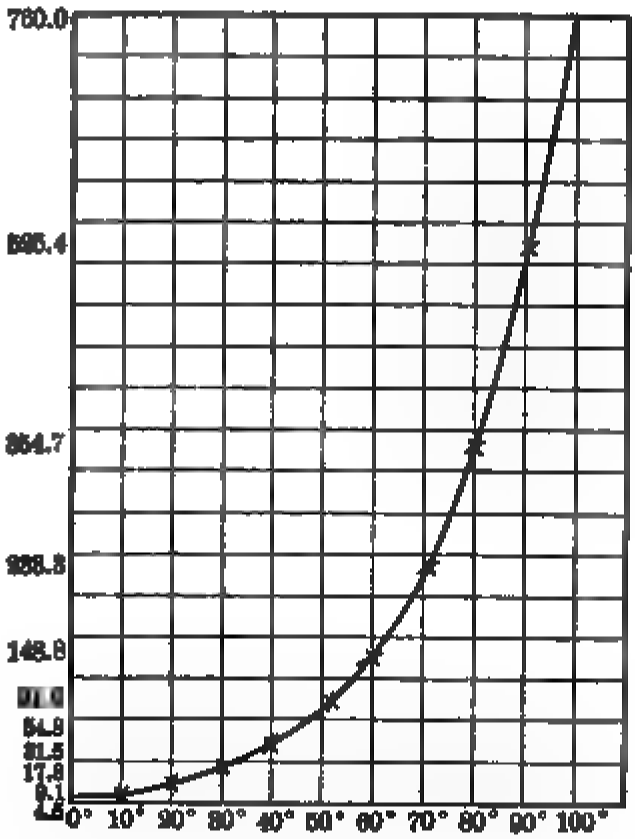


FIG. 199. — Boiling point varies with atmospheric pressure.

Near the boiling point a variation of 27 mm. in the atmospheric pressure causes the boiling point of water to vary one degree Centigrade. When the barometric pressure is reduced to 525.4 mm., water boils at 90° C. This is about the boiling point of water on a mountain 9000 ft. high. On high mountains it is difficult to cook vegetables by boiling unless covered vessels called *pressure cookers* are used. See Fig. 200. Since the steam cannot escape, the pressure rises and

FIG. 200. — Denver pressure cooker.

the boiling point is raised. It requires about twice as long a time to cook foods when the temperature is 90° C. as it does at a temperature of 100° C. At a temperature of 110° C. the time required is reduced to about one half that needed at 100° C. At an elevation of 900 ft., the boiling point of water is lowered about 1° C. A vessel of water under a bell glass from which the air is exhausted boils freely at room temperature. This principle is used for evaporating liquids that have a high boiling point, *vacuum pans* being used to accelerate the evaporation. The syrup from which sugar crystals are obtained is evaporated in vacuum pans to prevent scorching.

**225. Laws of Boiling.** *We may define the boiling point as that temperature at which the saturated vapor of the boiling liquid just equals the pressure upon its surface.* Several facts concerning boiling liquids may be summarized as follows:

1. *Every pure liquid has a definite boiling point under the same conditions.* Liquids are sometimes identified by determining the boiling point.

2. *The boiling point of a pure liquid does not change, but remains constant until all the liquid has vaporized.*

3. *The temperature of the boiling point rises as the atmospheric pressure increases, and falls as the pressure decreases.*

4. *Solids dissolved in liquids raise the boiling point. Gases dissolved in liquids usually lower the boiling point.*

**226. Distillation.** *Distillation is a complex process of vaporization and condensation.* An apparatus like that shown in Fig. 201 is often used in the laboratory. The liquid to be distilled is put in flask *A* and heated to boiling. *C* is a double-walled condenser through which cold water circulates. The vapor condenses in the inner tube and runs down into the receiver at *B*. Any substances that do not vaporize remain in the flask. Distillation is much used to purify substances that contain non-volatile impurities.

From mixtures such as crude oil a number of substances can be obtained by *fractional distillation*. Some of its most

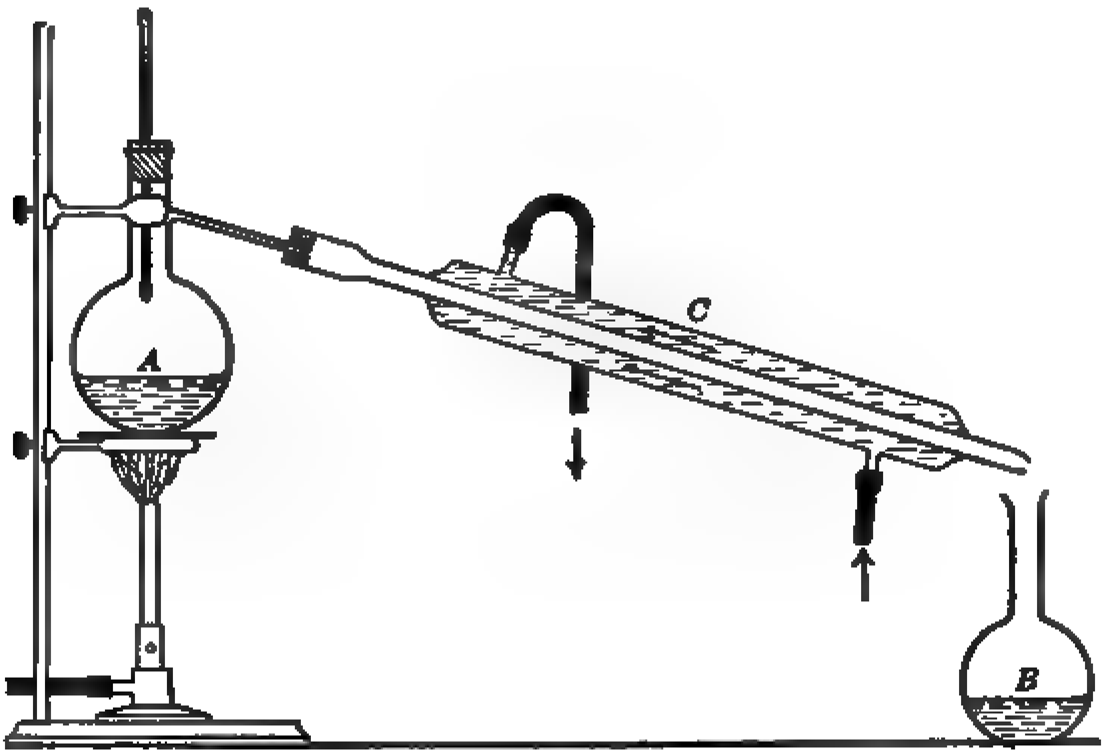



FIG. 201. — Distillation.

FIG. 202. — Fractional distillation of crude petroleum. (*Courtesy of Tidewater Oil Company.*)

important constituents are gasoline, naphtha, kerosene, lubricating oils, vaseline, and paraffin. Since these products have different boiling points, they may be separated by heating the crude oil and collecting the various distillates. See Fig. 202. Complex solids, such as wood and coal, yield many products by *destructive distillation.*

**227. Heat of Vaporization.** If we put a quart of ice water on a gas stove and heat it until it is all evaporated, we find that it takes more than five times as long to boil it away as it did to raise it to the boiling point. We know that it takes 100 calories of heat to raise 1 gm. of water from 0° C. to 100° C. Since heat must have been absorbed while the water was boiling away, we conclude that it must take more than 500 calories to vaporize one gram of boiling water. *The heat required to vaporize 1 gm. of a substance without changing its temperature is called its heat of vaporization.* More accurate methods than that used above show that the heat of vaporization of water is 536 calories per gram, or 965 B.T.U.'s per lb.

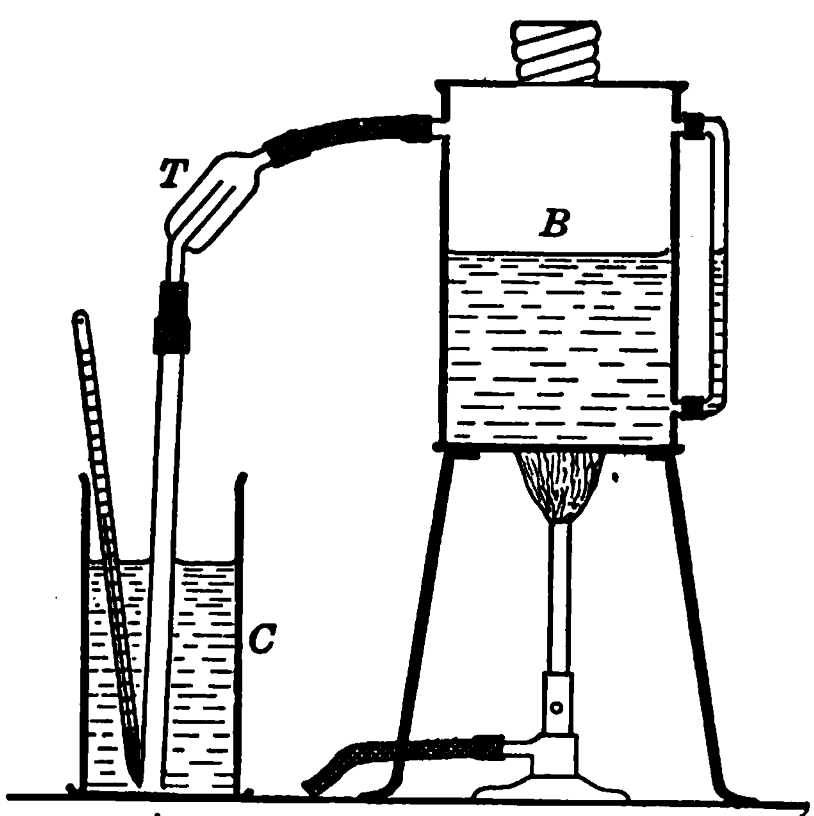


FIG. 203. — Heat of vaporization.

**228. Method of Finding Heat of Vaporization.** The method of mixtures is generally used to determine the heat of vaporization of a liquid. The calorimeter *C*, Fig. 203, is weighed and then filled two thirds full of water. The weight of the water is determined and also its temperature. Steam from the boiler *B* is then introduced. The trap *T* collects the water from the steam that condenses before passing into the calorim-

eter. When a sufficient quantity of *dry* steam has been introduced, the tube is removed, the temperature observed, and another weighing taken. The increase in weight equals the weight of steam introduced. Suppose we obtain the following data:

| | |
|---|---|
| Weight of calorimeter . . . . . . . . . | 120 gm. |
| Specific heat of calorimeter . . . . . . | 0.09 |
| Weight of water . . . . . . . . . . . . | 401 gm. |
| Weight of steam . . . . . . . . . . . . | 23.5 gm. |
| Initial temperature of water . . . . . . | 6° C. |
| Final temperature of water . . . . . . | 40° C. |
| Temperature of steam . . . . . . . . . | 100° C. |

Computations:

$120 \times (40-6) \times 0.09 = 367$ calories absorbed by calorimeter.

$401 \times (40-6) \times 1.00 = 13{,}634$ calories absorbed by water.

Total calories absorbed $= 14{,}001$.

When 23.5 gm. of steam condense, 23.5 gm. of water at 100° C. are formed.

$23.5 \times (100-40) \times 1.00 = 1410$ calories lost by water in cooling from 100° C. to 40° C.

$14{,}001 - 1410 = 12{,}591$ calories lost by 23.5 gm. of steam on condensing.

$12{,}591 \div 23.5 = 535.7$ calories, heat of vaporization.

**229. Heat Given Out on Condensation.** When steam or water vapor condenses it loses as much heat as was required to vaporize it. Every gram of steam that condenses in a radiator yields 536 calories of heat. This principle is used in steam heating systems. Steam produces a more severe burn than boiling water, not because its temperature is higher, but because every gram of steam loses 536 calories of heat upon condensing; it still has the same heating effect as an equal weight of boiling water.

**230. Cooling Effect of Evaporation.** Sprinkling the streets on a hot summer's day cools the adjacent air by evaporation. If water is poured on one hand, it will soon feel cooler than

the other. Heat is absorbed during the evaporation of the water. As the hand loses this heat, its temperature is lowered. Alcohol evaporates faster than water, hence it produces a greater cooling effect. The use of the alcohol sponge bath to reduce fevers is an application. Ether boils at about 35° C. If we put a few drops of water on a wooden block, place a watch glass containing a couple of teaspoonfuls of ether thereon, cover the whole with a bell glass, and exhaust the air rapidly, the ether will boil under reduced pressure. The very rapid evaporation of the ether takes heat from the water so rapidly that the watch glass will be frozen to the block.

**231. Artificial Ice.** The manufacture of artificial ice depends upon the principle of cooling by evaporation. The

FIG. 204. — Diagram of an artificial ice plant.

faster the evaporation, the greater the cooling effect. By using ammonia, a liquid whose boiling point at atmospheric pressure is −34° C., a very low temperature may be produced. At ordinary temperatures ammonia is a gas, but it may be easily liquefied by cooling and compression. Fig. 204 shows a diagram of a plant used to make artificial ice. The gas is compressed in the cylinder by the piston $P$, the heat of compression being absorbed by cold water. The liquid ammonia flows through the expansion valve $V$ into the coils $C$ and $C'$, which are immersed in brine. As it evaporates every gram of ammonia absorbs about 295 calories of heat from the brine, which is thus cooled below the freezing

point of fresh water. Cans of fresh water immersed in the brine are frozen in from 36 to 48 hours into cakes of solid ice.

In cold storage plants the brine is pumped through pipes in the storage rooms. Just as hot water flowing through pipes in a room warms it by radiation, so the circulation of the cold brine cools the room to any desired temperature.

**232. Liquefaction of Gases.** Some gases cannot be liquefied by pressure alone. Air, for example, must be cooled to −140° C. before any pressure, however great, will cause it to become liquid. The temperature to which a gas must be cooled before it can be liquefied by pressure alone is called the *critical temperature.* The pressure required to liquefy a gas at its critical temperature is called its *critical pressure*. By the use of high pressures and subsequent cooling by expansion all gases have been liquefied. Successive compressions are necessary in the case of gases that

FIG. 205. — Linde's apparatus for liquefying air

have a very low boiling point. Liquid air under atmospheric pressure boils at from −182° C. to −194° C., the variation depending upon the per cent of nitrogen present. Hydrogen boils at −253° C. Fig. 205 shows an apparatus that is sometimes used to liquefy gases.

**233. Effect of Heat on Water Shown Graphically.** Suppose we plot a curve to show what changes take place when ice at −10° C. is heated until it is all converted into steam under pressure at 120° C., using temperature changes as ordinates and heat units as abscissas. See Fig. 206. Since

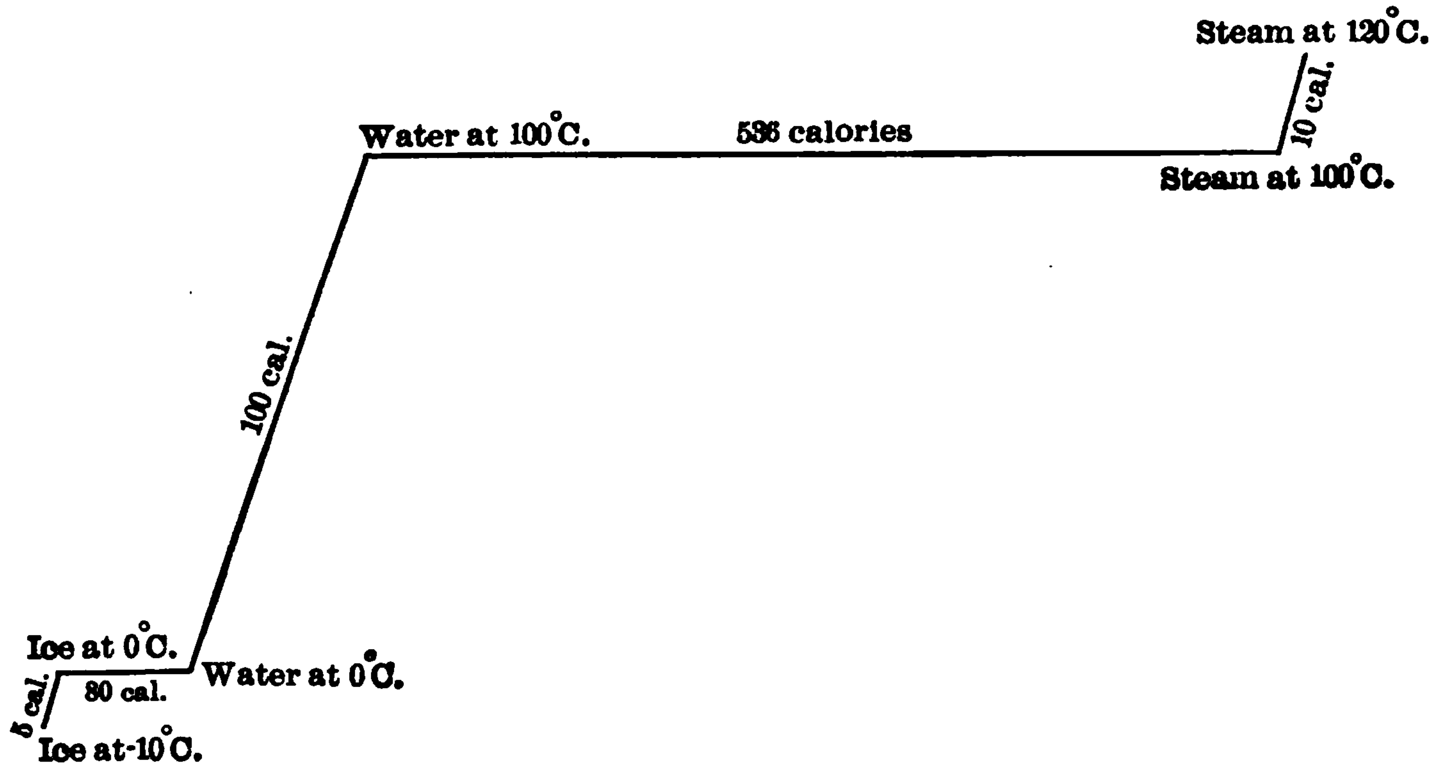



FIG. 206. — Heat absorbed during change of state and of temperature.

the specific heat of ice is 0.5, 1 gm. would absorb 5 calories in being warmed to zero degrees. 80 calories are absorbed in melting the ice. *Note that there is no temperature change.* 100 additional calories are needed to warm the water to the boiling point. Another change of state occurs, in which 536 calories of heat are absorbed. If the steam, which has a specific heat of almost 0.5, is under pressure, 10 calories will be used to heat 1 gm. from 100° C. to 120° C. The student will find this curve helpful in solving problems involving specific heat, heat of fusion, and heat of vaporization.

**234. Humidity.** Even at 32° F., or lower, some evaporation takes place. Therefore the air contains some water vapor at all times. The amount of *water vapor which the air can contain when saturated is its capacity.* Capacity, which is usually expressed in grains per cu. ft., varies with the temperature. Table 5 in Appendix B shows that a cubic foot of warm air can hold much more water vapor than a cubic foot of cold air.

Since collision with air molecules retards evaporation, the air is not always saturated. *The amount of moisture the air actually does contain is called its absolute humidity. The ratio of what it does contain to what it could contain,* or $\frac{\textit{absolute humidity}}{\textit{capacity}}$, *is the relative humidity.* A rise in temperature decreases the relative humidity. To illustrate, suppose the air holds 2 grains of vapor per cu. ft. on a day when the temperature is 32° F. The capacity, as shown by the table, is 2.113 grains. Therefore the relative humidity equals $2 \div 2.113$, or 94%. The air under such conditions will feel very damp. If the temperature is raised to 68° F., the amount of moisture will remain the same, but the capacity is increased to 7.48 grains per cu. ft. The relative humidity now equals $2 \div 7.48$, or 26%. The air will now feel very dry.

Again, suppose air at 84° F. contains 6.14 grains per cu. ft. The relative humidity equals $6.14 \div 12.356$, or 49%. The air has three times as much moisture as in the first case, but it feels drier because its *relative* humidity is fairly low. If this air were suddenly cooled to 62° F., the relative humidity would rise to 100%, and the moisture would begin to condense. *The temperature at which the water vapor in the air begins to condense is called the dew point.* Before precipitation of any kind can occur, the air must be cooled below the dew point. If the dew point is below 32° F., frost or snow will be formed.

When the relative humidity is below 50%, the perspiration evaporates quite rapidly and we feel more comfortable than at either a very low or a very high relative humidity. If the relative humidity is too low, the skin becomes dry and chafed. Too high a relative humidity is just as uncomfortable, especially when the temperature is high. The body cannot be cooled in hot weather unless the perspiration evaporates readily.

FIG. 207. — Hygrodeik. Dew point, absolute and relative humidity.

**235. The Wet-and-Dry-Bulb Thermometers.** The relative humidity may be found by using two thermometers, one having a dry bulb, the other a wet bulb. When the air is dry, the moisture evaporates rapidly from the wet bulb, lowering its temperature. The faster the evaporation, the greater the difference of temperature between the two thermometers. Tables have been constructed for showing the relative humidity directly from the difference between the two thermometer readings. The hygrodeik, Fig. 207, is an application of the same principle. See table 13 of Appendix B.

## SUMMARY

The calorie is the amount of heat required to raise the temperature of 1 gm. of water 1° C. In heat exchange, calories lost equal calories gained.

The specific heat of a substance is the number of calories required to raise the temperature of 1 gm. of that substance 1° C. Weight in gm.×change in temperature (Centigrade)×specific heat equals calories. Weight in lb.×change in temperature (Fahrenheit)× specific heat equals B.T.U.'s.

Fusion is the process of changing from the solid to a liquid state. The temperature at which the change occurs is the melting point. Increase in pressure raises the melting point of substances that contract when solidifying, and lowers the melting point of substances that expand during solidification.

To change 1 gm. of ice at 0° C. to water at the same temperature requires 80 calories; the same amount of heat is lost when 1 gm. of water freezes.

The boiling point of a liquid may be defined as the temperature at which the pressure of its vapor equals the atmospheric pressure. An increase in pressure rasies the boiling point; a decrease in pressure lowers the boiling point.

Distillation, a process consisting of evaporation and condensation, is used to purify substances or to separate liquids having different boiling points.

To change 1 gm. of water at 100° C. into 1 gm. of steam at the same temperature requires 536 calories; the same amount of heat is set free when the steam condenses.

Evaporation requires heat. This heat is taken from the surrounding medium, thus lowering its temperature. Artificial ice is made by the application of this principle.

The amount of water vapor air *can* hold at a given temperature is its capacity; the amount of water vapor the air *does* hold is its absolute humidity; absolute humidity divided by capacity equals relative humidity.

## QUESTIONS AND PROBLEMS

**1.** Why is the climate along the southern shores of Lakes Erie and Ontario suitable for fruit-growing?

**2.** Why does snow "pack"? Why is it impossible to make snowballs if the temperature is much below 32° F.?

**3.** Why do streets dry so rapidly on a windy day?

4. Which cools a refrigerator more, 1 lb. of ice or 1 lb. of ice water? Explain.

5. Food is sometimes kept in thick-walled porous vessels which have been immersed in water before using. Under what atmospheric conditions are such "iceless" refrigerators efficient?

6. Does fanning cool the face when one is not perspiring? Explain.

7. Why is it difficult to keep cool in summer when the relative humidity is above 90%?

8. Is water any hotter when boiling vigorously in an open vessel than when boiling slowly? Try to find in the answer to this question a suggestion as to one method of reducing gas bills.

9. Why do clothes sometimes "freeze dry"?

10. Why does steam produce a more severe burn than boiling water at the same temperature?

11. The steam that enters a radiator may be the same temperature as the water that leaves it. How has the room been warmed?

12. What is the boiling point of water when the barometer reads 740 mm.?

13. A thermometer immersed in free steam reads 100.6° C. when the barometer reads 765 mm. How much is the thermometer in error?

14. A calorimeter weighs 110 gm. Its specific heat is 0.09; if its temperature is 10° C., how many gm. of water at 40° C. must be poured into it to raise its temperature to 26° C.?

15. 300 gm. of metal at 98° C. are mixed with 526 gm. of water at 20° C. The temperature rises to 26° C. Find the specific heat of the metal.

16. A calorimeter, specific heat 0.09, weighing 80 gm., contains 40 gm. of water at 20° C. A platinum ball weighing 60 gm. is taken from a furnace and plunged into the water. The temperature of the water rises to 25° C. What was the temperature of the furnace?

17. How many calories are required to melt 42 gm. of ice and raise the temperature of the water thus formed to 40° C.?

18. How many calories of heat are furnished by 20 gm. of steam on condensing? How many additional calories are liberated when the water is cooled to 60° C.?

**19.** How many calories of heat are set free by 10 gm. of steam on condensing, cooling to 0° C., and then freezing?

**20.** How many gm. of ice can be melted by 40 gm. of steam?

**21.** How many gm. of ice at 0° C. are needed to lower the temperature of 1000 gm. of water from 80° C. to 40° C.?

**22.** What will be the final temperature when 20 gm. of ice at 0° C. are mixed with 400 gm. of water at 30° C.? (*Hint.* Let $x$ equal the final temperature. $400(30-x)$ times 1.00 equals calories lost. $20 \times 80$, plus $20(x-0)$, times 1.00 equals calories gained.)

**23.** 100 gm. of ice, 300 gm. of ice water, and 20 gm. of steam are mixed. Find the resulting temperature.

**24.** 40 gm. of steam, 100 gm. of water at 100° C., 200 gm. of ice, and 400 gm. of ice water are mixed. Find the resulting final temperature.

**25.** 10 gm. of steam at 150° C. are mixed with 200 gm. of ice water and 60 gm. of ice at −20° C. Find the resulting temperature.

*Suggested Topics.* Bomb Calorimeter. Pressure Cooking. Sterilizers and Autoclaves. Refining of Sugar. Dehydration of Foods. Iceless Refrigerators. Humidifiers.

## CHAPTER 12

# HEAT — METHOD OF DISTRIBUTION

**236. Distribution of Heat.** The sources of heat have already been studied; it is now very practical to inquire how heat is distributed. A radiator in one corner of a room furnishes heat to the entire room. From the furnace in the cellar there must be a secondary distribution of heat to all parts of the house. If we know how heat is transmitted, then it may be possible to hasten or to check such distribution. Three distinct methods of transferring heat energy are known: (1) *conduction,* which occurs readily in most solids; (2) *convection,* which is applicable to liquids and gases; and (3) *radiation,* which is the transmission of heat energy by waves set up in the ether.

**237. Conduction in Solids.** If the bowl of a silver spoon is put into a cup of hot coffee, soon the handle becomes hot enough to burn the fingers. If we hold one end of a stove poker while the other end is inserted in a bed of live coals, in a few minutes the entire poker becomes too warm to be held comfortably. *Such transmission of heat from molecule to molecule is called conduction.* The molecules of the coals are in rapid vibration. The molecules of the poker which are adjacent to the coals are receiving heat energy, which is transmitted by them to other molecules.

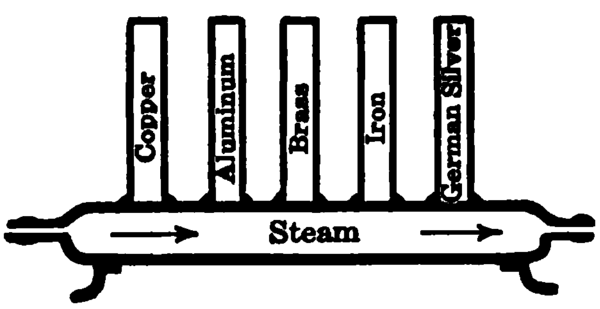



FIG. 208. — Conduction of heat.

Most solids, especially the metals, are good conductors of heat. The rods of the conductometer, Fig. 208, are made

of different metals covered with paraffin. When steam is passed through the base of the apparatus, the paraffin melts most quickly on the best conductor. The order of conductivity of the five metals used in the experiment is as follows: copper, aluminum, brass, iron, and German silver. Silver is the best conductor known; copper and aluminum are much better conductors than other common metals. German silver, which is now commonly called nickel silver, does not contain any silver; it is an alloy of copper, zinc, and nickel. It is not a good conductor. Wool, cotton, silk, and other porous solids are rather poor conductors. Sawdust is a poorer conductor than solid wood, on account of the air spaces between the particles. See table 11 of Appendix B for the relative conductivity of some common substances.

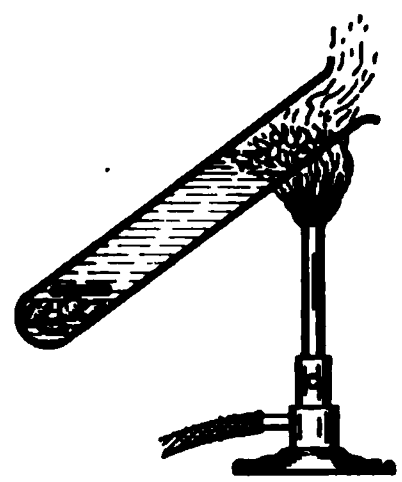


FIG. 209. — Liquids are poor conductors.

**238. Conductivity of Liquids and Gases.** If we put a piece of ice in the bottom of a test tube, weight it, and then fill the tube nearly full of water, the water at the top of the tube may be boiled for some time without melting the ice. See Fig. 209. This experiment shows that water is a poor conductor of heat. A still more sensitive test can be made by the use of the apparatus of Fig. 210. The bulb *B* of an air thermometer is surrounded with water in a large funnel. The stem of the thermometer dips into a bottle containing some colored liquid. Ether is poured on the surface of the water and set on fire. The air thermometer is very sensitive, but the liquid column *C* is lowered only a trifle. The water layer evidently does not conduct the heat from the burn-

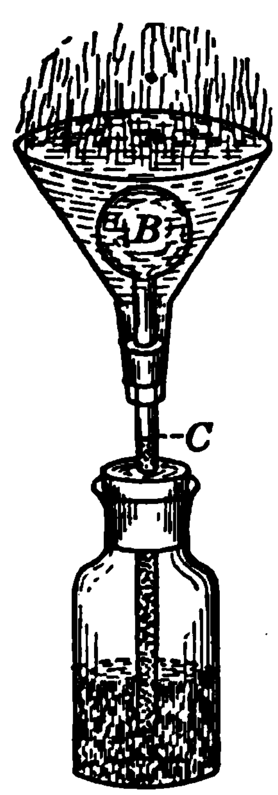
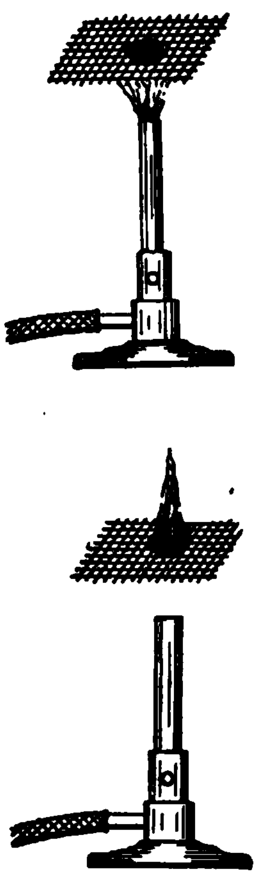



FIG. 210. — Use of air thermometer to show poor conductivity of liquids.

ing ether to the bulb of the thermometer. From both of these experiments we must conclude that water is a poor conductor; other liquids are also poor conductors.



Gases are poorer conductors than liquids. Silver conducts heat more than 800 times as rapidly as water, and almost 20,000 times as fast as air. Non-conducting layers of air in porous solids are largely responsible for their poor conductivity. A vacuum is practically a non-conductor.

**239. Applications of Conductivity.** When a wire gauze is held over a bunsen burner, the gas may be lighted either above or below the gauze. See Fig. 211. The gauze conducts the heat away so rapidly that the gas on the opposite side is not heated to its kindling temperature. The miner's safety lamp, invented by Sir Humphry Davy, depends upon this principle, Fig. 212. The flame of the lamp is surrounded by wire gauze, which prevents explosive gases that may be present in the surrounding atmosphere from being ignited.

Fig. 211. — Metal gauze conducts heat so rapidly that gas is not enkindled.

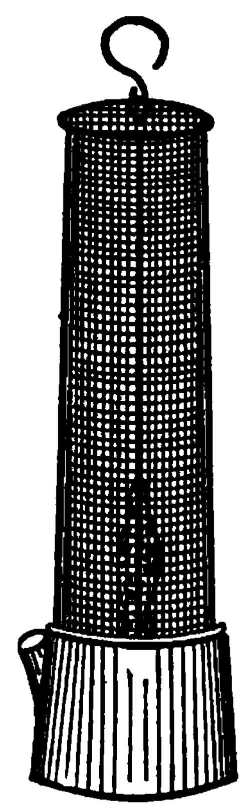


Fig. 212. — Davy safety lamp.

The *thermos* bottle is made of glass blown with double walls, Fig. 213. The air is exhausted from the space between the walls. Since a vacuum is a non-conductor, a hot substance put in the bottle retains its heat; a cold substance put in the bottle remains cold, since it cannot receive heat from the outside. The glass is silvered to prevent the transmission of radiant heat.

The *fireless cooker* is made of non-conducting material. In one type the food to be cooked is first heated to boiling

and then put inside the fireless cooker. Since the loss of heat by conduction is small, the food is slowly cooked by the heat which is thus conserved. In some types of fireless cookers, soapstone discs having a high thermal capacity, are heated to a high temperature and put into aluminum containers with the dish of food. The container is surrounded with non-conducting material to prevent the loss of heat by conduction. The heat from the discs is thus used to cook the food.

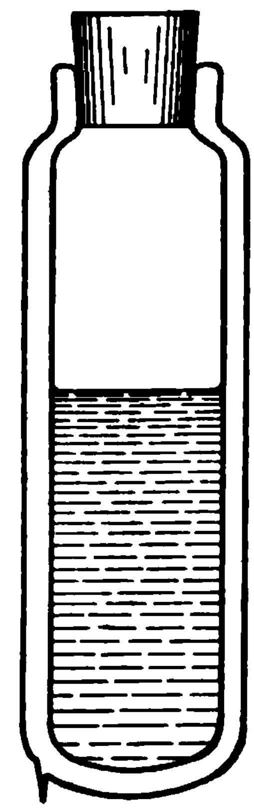


FIG. 213. — Thermos bottle. (Sectional.)

**240. Conductivity and Sensation.** In removing a pan of bread from the oven, we get a more severe burn if we touch the pan than by touching the bread. Both have the same temperature, but since the metal is the better conductor, it transmits heat to the hand more rapidly. The bare floor feels colder in winter than a rug, because it takes heat from the body more rapidly.

Clothing does not afford us any warmth in winter, but it prevents the heat of the body from escaping. That kind of clothing which is made of the poorest conducting material seems warmest. Furs are very warm because they contain layers of non-conducting air. Two light garments are warmer than a single heavy one because there is a layer of non-conducting air between them. Silk and wool are poorer conductors than cotton and linen.

**241. The Principle of Convection.** We have learned that substances expand when heated and that their density is correspondingly decreased. Let us add a few particles of sawdust to a beaker of water and heat the beaker near one side, as in Fig. 214. The water directly over the flame is more highly heated; it expands, and is pushed up by the heavier and colder water from $A$. The circulatory movement which the water thus acquires can be observed

by the movement of the sawdust particles. Convection currents may be set up in gases in exactly the same manner. *The transmission of heat by the movement of the heated masses is known as convection.*

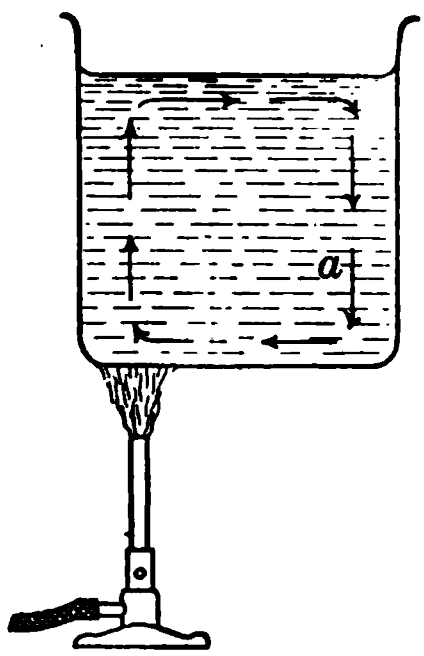


FIG. 214. — Convection currents.

**242. Ventilation.** The whole plan of ordinary ventilation depends upon convection. As the air is warmed by breathing, it becomes lighter, and is pushed upward by the heavier, cooler air. There should always be two openings in a room, one for the entrance of fresh air, and the other for the exit of foul air. Three diagrams are shown in Fig. 215. A little study of these diagrams shows clearly that one opening should be near the ceiling, and the other near the floor. In the ventilation of mines and large buildings compressed air is extensively used.

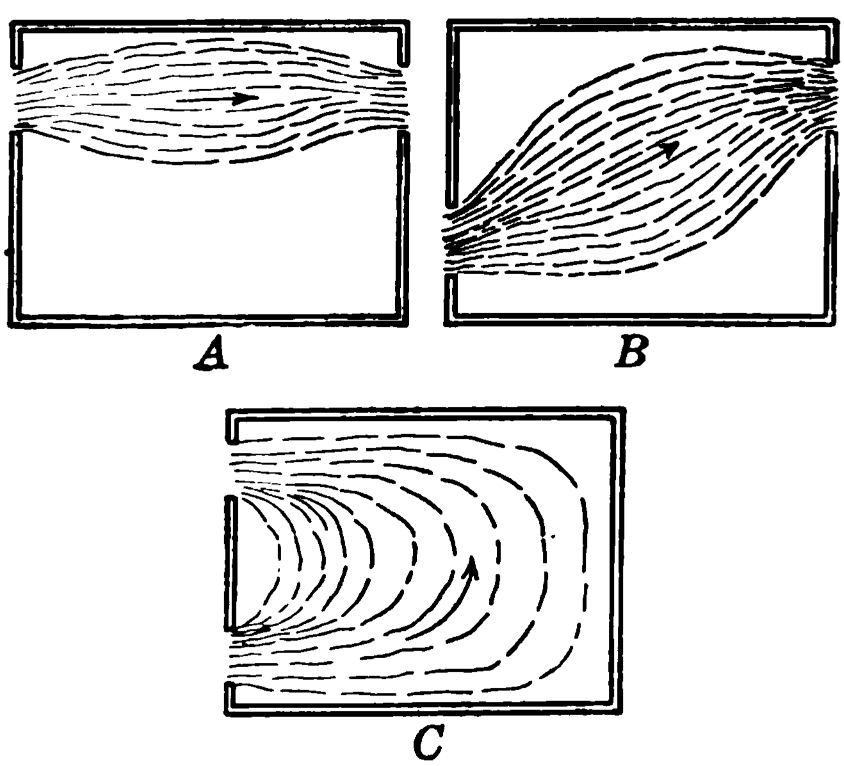


FIG. 215. — Arrangement of openings for ventilation.

**243. Draft of a Chimney.** When a fire is started in a stove or furnace, the air above the fire is heated and expands. The cold, heavy air outside pushes the heated air and the hot gases formed by combustion up the chimney. A tall chimney produces a better draft than a short one, since there is a greater difference in weight between the hot gases inside the chimney and the same volume of cold air outside. The wind

blowing across the top of a chimney also aids in producing a draft. See § 60.

**244. Land and Sea Breezes.** Since the land has a lower specific heat than water and it is not so mobile, it heats more rapidly in the daytime. The air over this heated area is pushed upward by the cooler air from the sea; therefore about the middle of the forenoon a cool sea breeze begins to blow toward the land, Fig. 216.

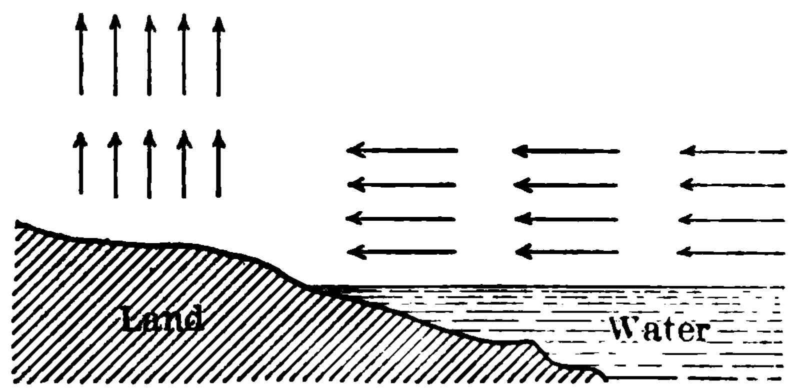



FIG. 216. — Sea breezes.

At night the land cools more quickly, the warmer air over the water is forced upward, and a land breeze is produced. Fishermen along the coast go to sea at night with the land breeze, and return in the forenoon with the sea breeze.

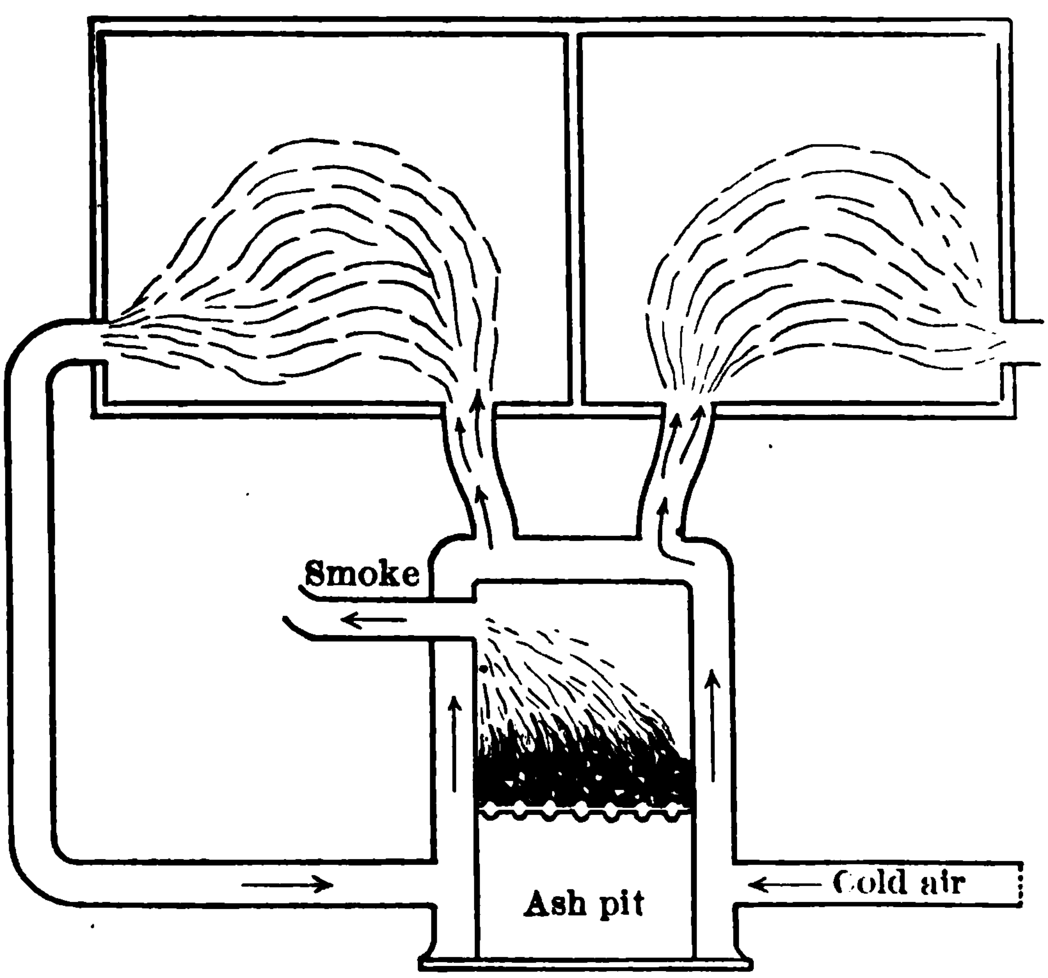



FIG. 217. — Hot-air heating system.

*Monsoons* are huge *seasonal* land and sea breezes. In summer, the land area is intensely heated and the wind blows toward the land continually. In winter, the conditions are reversed, and the wind blows toward the sea.

The *trade winds* are also produced by convection currents. The direct rays of the sun in the vicinity of the equator produce upward air currents. The trade winds then blow toward the equator throughout the year. They do not blow due north and south, since they are deflected toward the west by the rotation of the earth on its axis.

**245. Heating Systems.** In *hot-air* heating systems, the heat is distributed by convection currents. The cold air usually enters from out-of-doors directly, Fig. 217, circulates around the fire-box, and then rises to the rooms. A part of the air then escapes through doors and windows, while in some systems a part returns to the furnace, where it is mixed with fresh air and reheated.

Fig. 218. — Pipeless hot-air furnace.

Some hot-air furnaces now in use are *pipeless*. Such furnaces depend entirely on convection currents to distribute the heat to all parts of the house. The furnace of Fig. 218 has one large register directly over the furnace. The hot air rises from the center of the register, circulates through the rooms by way of transoms and doors, and returns to the furnace to be reheated. The register is composite, having an opening in the center for the heated air, and an annular opening surrounding the former through which the air is returned for reheating.

The principle of convection currents is also used in *hot-water* heating systems. The water which circulates around the fire-box is heated and rises to the radiators. Here it loses heat to the room by conduction and radiation, and then returns to the bottom of the furnace to be reheated. An expansion tank is connected with the system to accommodate the increased volume of water when it is heated, and also to act as a safeguard for the escape of steam if the water should boil. The arrows of Fig. 219 show the direction of the circulation.

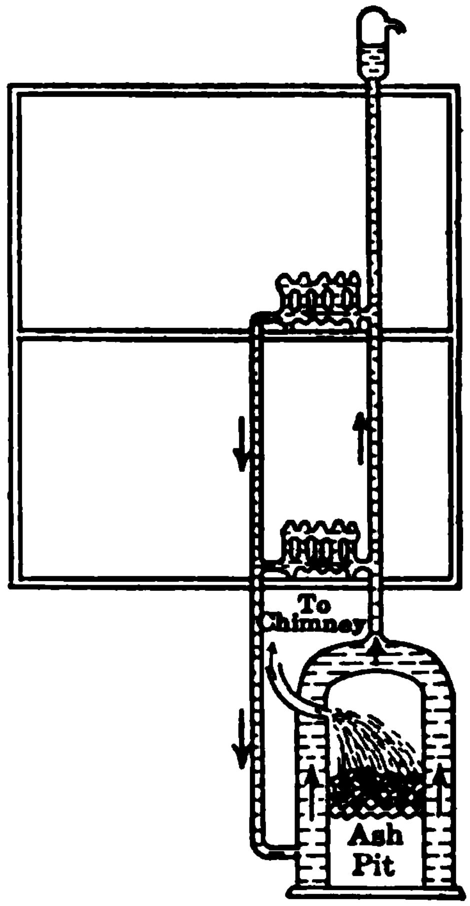



FIG. 219. — Hot-water heating system.

In *steam-heating* systems the water is heated to boiling, and the steam rises to the radiators, where it condenses. For every gram of steam that condenses 536 calories of heat are set free; this heat is utilized in warming the room. After condensation occurs, the water returns to the boiler, either through another set of pipes, or, in many cases, through the same pipe. Fig. 220 shows the arrangement of furnace and radiators in a steam-heating system.

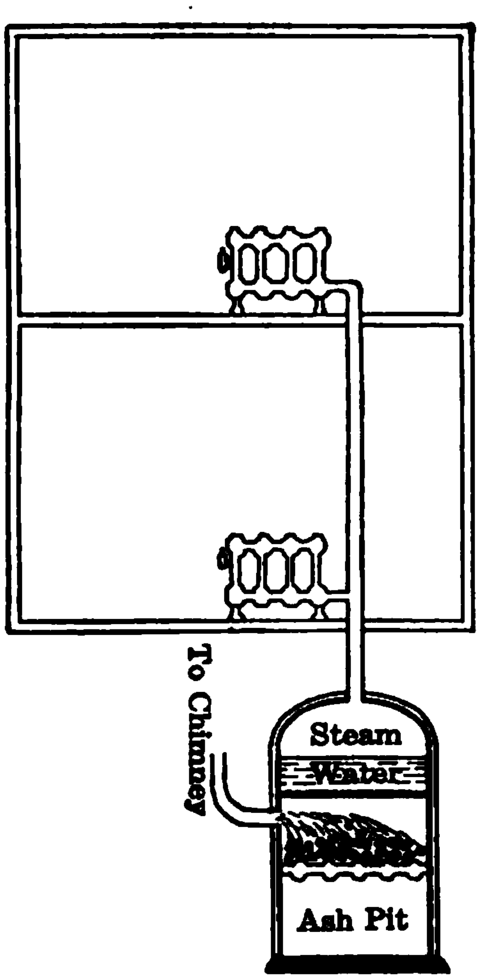



FIG. 220. — Steam-heating system.

**246. Vacuum Valves.** If the valves on steam radiators work properly, they close when all the air is expelled, and no steam can escape. Very often such valves are

replaced by vacuum valves which act automatically to prevent the air from entering the radiator. As the fire dies down and the steam condenses, there is a partial vacuum inside the radiating system. Since water evaporates more readily under reduced pressure, it is easy to get up steam with a vacuum system. In mild weather, or after the fire is banked, hot vapors much below 100° C. are given off by such a steam-heating system, Fig. 221.

Fig. 221. — Vacuum valve.

**247. The Percoplate Boiler.** The efficiency of the average steam-heating boiler is usually not more than 30 or 40%. This means that considerably more than half of the 10,000 to 14,000 B.T.U.'s which a pound of coal may furnish either pass up the chimney as waste heat, or they are used to heat water which is never converted into steam. In the last paragraph we discussed the vacuum valve as a coal saver. Tests carried out by one of our leading schools of technology show that the percoplate boiler has an efficiency of over 75%. The inventors of this boiler got their idea from the coffee percolator. About one gallon of water in the part of the boiler marked *B*, Fig. 222, is heated to boiling within a

few minutes after the fire is enkindled. As this boiling water rises to the top of the boiler it spurts out over the hot metal plate shown at *A*. Here a part of it is vaporized, while the remainder flows down to the heated plate *C*, where it is converted into steam. The arrows show how the hot gases from the burning fuel circulate around the metal plates and keep them at a high temperature. The small tank at the right supplies water to keep the levels adjusted. The advantage of this boiler lies in the fact that only a small quantity of water is heated at one time. The ridges on the metal plates serve as baffle walls, forcing the water to take a circuitous path over the plate, thus greatly increasing the relative heating surface.

FIG. 222. — Percoplate boiler.

**248. Hot-water Tank.** The method of heating water for the kitchen, bath, or laundry differs little from the method

of heating houses by hot water. Cold water enters the tank, Fig. 223, through a pipe which reaches nearly to the bottom. Convection currents are set up in the heating coil, and the hot water is pushed up to the top of the tank. When the hot water is drawn off at the top of the tank, cold water enters at the bottom and does not mix with the heated water.

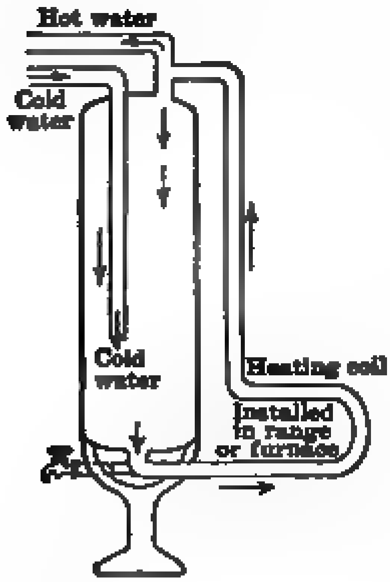


FIG. 223. — Hot-water tank.

**249. Radiation.** When the hand is held in front of a fireplace, Fig. 224, it is warmed by radiation. In the same manner we receive heat from the sun. Since heat is a form of energy produced by the motion of the molecules, waves are set up in the surrounding medium. Huygens advanced the wave theory to account for the transmission of radiant energy. Radiations travel through a vacuum, so he presupposes the existence of a very subtle medium which pervades all space and transmits radiant energy. This medium is called *ether*. It is supposed to be an invisible fluid, so very rare that it cannot be weighed or measured; it easily penetrates intermolecular spaces. *The absorption of radiant energy produces heat in the absorbing medium. Substances easily penetrated by the ether waves are little warmed by their passage.*

FIG. 224. — Heating by radiation.

**250. Absorption, Reflection, and Radiation of Heat.** When heat waves are incident upon an object, a part are reflected, a part may be transmitted, and the rest are absorbed. Polished metals are the best reflectors known; hence they are very poor absorbers of heat. A poor absorber of heat is also a poor radiator. A roughened tea-kettle absorbs heat more readily than a highly polished one; it also loses heat faster by radiation.

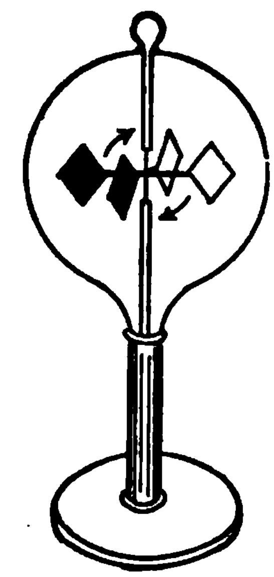


Fig. 225. — Crookes' radiometer.

The color of a substance also affects its absorbing power. A black surface absorbs heat faster than a white one. Hence light-colored garments are cooler in summer sunshine than black ones. Lampblack is the best absorber known and also the best radiator.

Crookes' radiometer may be used to demonstrate these facts. It consists of a partially exhausted bulb, in which is suspended a light aluminum wheel that has a set of vanes in its circumference. Each vane is polished on one side and covered with lampblack on the other. When exposed to a source of radiant energy, heat is absorbed more rapidly by the black surfaces. The adjacent air is more highly heated and rebounds with a greater velocity from the black surfaces, thus exerting greater pressure and causing the wheel to rotate in the direction shown in Fig. 225.

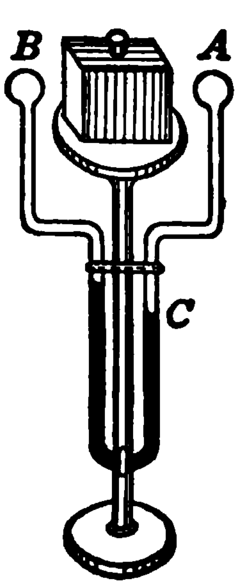



Fig. 226. — Leslie's cube and differential thermometer.

By the use of Leslie's cube and a differential thermometer, Fig. 226, it may also be shown that a black surface radiates heat faster than a white one. Surfaces of the cube are painted different colors. It is filled with hot water and supported so that the black face will be the same distance from bulb *A* of the thermometer that the white face is from bulb *B*. Since bulb *A* is heated more rapidly

by radiation from the black surface, the air within this bulb expands more and forces the liquid $C$ down the tube.

**251. Laws of Radiation.** *Radiant energy travels in straight lines at a velocity of about 186,000 miles per second.* When the moon comes between the earth and the sun so that the sun is eclipsed, both the heat rays and light rays are cut off at the same time.

*The intensity of radiant heat energy is proportional to the temperature of the source, and inversely proportional to the square of the distance.* A person sitting 6 ft. from a fireplace receives only one fourth as much heat as a person 3 ft. away.

*The rate of cooling by radiation is proportional to the difference between the temperature of the cooling body and the surrounding medium.* This is known as Newton's law of cooling. A body at 60° C. cools twice as fast as one at 50° C. when both are in an atmosphere at 40° C.

**252. Heat Transparency.** When the ether waves produced by radiant energy pass through a substance without heating it, the substance is said to be *diathermanous.* Substances opaque to heat are *athermanous.* Dry air is quite transparent to heat, but air containing much water vapor is much more opaque. Clouds absorb heat as it travels from the sun to the earth, and they prevent, to a great extent, the loss of heat from the earth by radiation.

Some substances are transparent to light, but opaque to heat. Alum is an example. Conversely, iodine solution is opaque to light, but transparent to heat.

Heat from the sun readily comes in through glass windows, but heat from the radiators does not pass out through glass readily. If the temperature of the source of heat is very high, its waves are short and very penetrating. The heat waves given off from a radiator are long waves and much less penetrating. Glass is used for covering greenhouses

and " cold frames "; the heat from the sun passes in through the glass, but there is little loss by radiation.

## SUMMARY

Heat may be transmitted by conduction, convection, and radiation. Solids conduct heat better than liquids or gases. Convection does not occur in solids.

Good conductors feel hotter than they really are, if their temperature is higher than that of the hand; when their temperature is lower than the hand, they feel colder.

Convection depends upon the fact that fluids expand when heated. Ventilation systems, hot-air and hot-water heating systems, and atmospheric circulation all depend upon convection currents.

Good absorbers of heat are good radiators. Good reflectors are poor absorbers and poor radiators.

## QUESTIONS AND PROBLEMS

1. Why does wrapping ice in a woolen blanket keep it from melting rapidly? Is ice of much value in a refrigerator unless it melts? Explain.

2. Why does a chimney " draw "? How does the height of the chimney affect the draft? Why does a chimney " draw " better on a clear, cold day than in damp, cloudy weather? Explain why a chimney " smokes " when a new fire is started.

3. Why are houses built with hollow walls?

4. Why do stove lifters and pokers usually have wooden or coiled wire handles?

5. Why do workmen around furnaces wear woolen clothing even in summer?

6. How does snow protect the grass in winter?

7. In making ice-cream, why is the cream usually put in a metal container and the ice in a wooden vessel?

8. Is it economy to keep stoves highly polished? Explain.

9. Why does dew or frost seldom form on cloudy nights?

10. On high mountains the sun is exceedingly hot in the daytime, but the temperature usually falls below freezing at night. Explain.

**11.** Why does it rain nearly every afternoon in the equatorial regions?

**12.** Why is it necessary for a radiator to have more sections when used with hot water than with steam heat?

**13.** Does tea cool more quickly in a tarnished metal pot or in a highly polished one?

**14.** Which is warmer, cotton clothing or linen? Why?

**15.** Why does mist often form in the receiver of an air pump?

**16.** Water kept in earthenware jars is much cooler than the surrounding air. Explain.

**17.** Why is silvered glass used in making thermos bottles?

**18.** Two pieces of cloth are laid upon the snow. One of them is black; the other, white. The black one sinks into the snow faster on a sunshiny day. Why? If we cover the black one with powdered alum and the white one with powdered iodine, the condition will be reversed. Explain.

**19.** In what way do double windows save fuel?

**20.** Why are steam-pipes in the basement covered with asbestos or magnesia?

**21.** Why does the tongue or a moistened finger freeze to a cold metal, but not to wood of the same temperature?

**22.** Is it economical to have steam radiators highly polished? Would it be economical to have them painted black?

*Suggested Topics.* Fireless Cooking. Advantages and Disadvantages of Various Heating Systems.

## CHAPTER 13

# HEAT AND WORK

**253. Heat and Work.** Friction and impact are both sources of heat. Friction is also the result of wasted work; therefore energy spent in overcoming friction is transformed into heat energy. Joule devised a method for finding out how much work would have to be done to produce one British thermal unit of heat. He used paddle wheels turned by weights falling through a known distance. The weight times the distance equaled the work done. No useful work was accomplished, since the paddles merely heated a known weight of water by friction. The rise in temperature of the water enabled him to calculate the amount of work needed to produce one British thermal unit of heat. He found that 772 ft. lb. of work are equivalent to one B.T.U.

Recent measurements show that 778 ft. lb. is a more accurate figure. In the Metric System *this is equivalent to 427 gram meters of work per calorie.* In terms of work the calorie may now be defined as $4.19 \times 10^7$ ergs. Since wasted work is converted into heat, conversely heat energy can be changed into mechanical energy, which is capable of doing work. One small calorie can do 427 gram meters of work. This is called *the mechanical equivalent of heat.*

**254. How Heat Is Converted into Work.** Biologists tell us that a thick slice of bread, when oxidized, furnishes 100 large Calories of heat. Suppose all this heat is converted into muscular energy; it could do 42,700,000 gm. m. of

work, sufficient to enable a man weighing 150 lb. to climb a mountain 2000 ft. high. A part of our food is used to maintain the body temperature, a portion is needed for nutrition and repair, while a third portion is oxidized to furnish heat for muscular energy.

*Courtesy of J. A. Randall.*
FIG. 227. — Energy diagram.

For mechanical purposes, the production of steam and the explosion of gasoline vapor are two of the most common methods of changing heat energy into mechanical energy. When water is converted into steam, it expands about 1600 times and exerts pressure in all directions. When gasoline vapor and air are mixed and ignited, an explosion occurs and pressure is exerted. One gram of good coal produces 8000 calories when burned, and one pound produces about 15,000 British thermal units. If all this heat could be converted into work, one pound of good coal would be equivalent to 15,000 times 778 ft. lb., or 11,670,000 ft. lb. of work. For every pound of coal burned per hr., we should get about 6 H.P. continuously. In practice, the ordinary steam engine uses about 1.5 lb. of coal to produce 1 H.P. per hr., an efficiency of about 11%. Some of the most efficient steam

engines use 0.8 lb. of coal per H.P. hr., an efficiency of about 20%.

Such low efficiency is not surprising if we consider that nearly 30% of the heat energy goes up the chimney during combustion. About 50% of what remains is lost from the fact that not all the expansive force of the steam can be utilized. The diagram of Fig. 227 shows how the heat energy is sometimes distributed in a simple power plant.

Fig. 228. — Steam engine cylinder.

**255. Simple Steam Engines.** When water boils the steam that is formed exerts great expansive force. The walls of the boiler must be made very strong to resist this force. By referring to the diagram of Fig. 228, we can understand the principle of the simple steam engine. As the steam comes from the boiler it enters the steam chest through the pipe $E$; it enters the right end of the cylinder and as it expands, the piston $P$ is forced toward the left. The spent steam in the left end of the cylinder passes out

through the exhaust at $O$. The valve $V$ then slides to the right, the steam enters the left end of the cylinder, and forces the piston to the right. In this way the piston is pushed to and fro alternately. The student should notice that the two openings in the cylinder are connected alternately with the steam chest by the slide valve. This valve operates so that one opening is connected with the exhaust when the other is connected with the intake.

In the *non-condensing* engine the exhaust steam escapes into the air. Of course it encounters a resistance of about 15 lb. per sq. in., due to the atmospheric pressure. This backward pressure means that a higher pressure must be maintained in the boiler to do the required work. Hence such engines are called *high-pressure* engines. Most stationary engines are fitted with a condenser, in which the exhaust steam is condensed by a spray of cold water. The vacuum produced in this way is sometimes so perfect that the back pressure is reduced to only 1 lb. per sq. in. A boiler pressure of 150 lb. per sq. in. will thus do approximately the same work, when the engine is fitted with a condenser, as 164 lb. of pressure when used with the non-condensing type. Locomotive engines are usually high-pressure, or non-condensing engines.

**256. The Boiler.** If an ordinary wash boiler is heated over a gas range, steam is produced, but the efficiency is very low because so little surface is exposed to the flame compared with the amount of water that is heated. The boilers used to furnish steam for engines are designed to have the fire and flames come in contact with as large a surface as possible. Two types of boilers are used, the *fire-tube* and the *water-tube*. In the latter type, which is often used with stationary engines, the flames play against the water reservoir and also around a large number of water-filled tubes which are connected with the reservoir. In the fire-tube type, which is used on locomotives, the flames are sucked

FIG. 229. — Locomotive diagram. *A*. Throttle. *B*. Sandbox. *C*. Smokestack. *D*. Steam pipe. *F*. Flue, or boiler tube. *G*. Sectional brick arch, to protect flues. *H*. Reverse gear rod. *L*. Piston valve. *M*. Piston in cylinder. *W*. Drive wheels.

From the diagram, it is evident that most of the weight of the locomotive rests on the drive wheels. This enables the wheels to grip the track more firmly, but still the drive wheels of a locomotive sometimes spin around rapidly when the latter is attempting to start a heavy train. Can you explain this? What is the purpose of the sandbox on a locomotive?

A large labeled diagram of the locomotive may be obtained from *Railway & Locomotive Engineering*, 114 Liberty Street, New York.

from the fire-box through long horizontal tubes that are surrounded with water. The exhaust steam escapes through the smokestack and produces a powerful draft. The locomotive diagram of Fig. 229 shows the arrangement of the fire-box and the flues.

With stationary engines the exhaust steam is often used to preheat the water entering the boiler. Such an arrangement is called a *feed water heater*. It is also possible to utilize the heat from the fuel gases for the same purpose, such a device being known as an *economizer*. Both methods increase the efficiency.

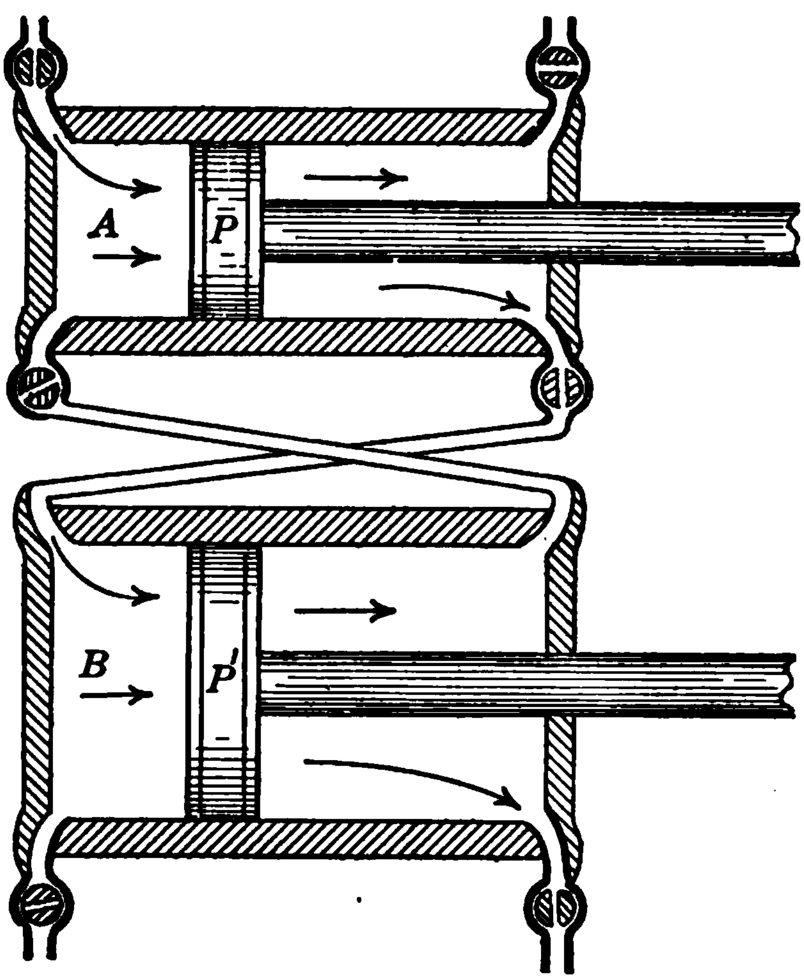



FIG. 230. — Double-expansion engine.

**257. Compound Engines.** Very often, however, locomotives are equipped with compound engines. See Fig. 230. The partially spent steam from cylinder $A$ passes into cylinder $B$. Here it expands still further, doing useful work on the piston $P'$. Such an engine is known as a *double-expansion* engine. Triple-expansion and even quadruple-expansion engines are sometimes used.

**258. The Cam or Eccentric.** In Fig. 228 we saw how the steam drives the piston forward and backward with a reciprocating motion. In the transmission of energy by belt wheels or in the case of the drive wheels of a locomotive, it is necessary to change such to-and-fro motion into a rotary motion. This is easily accomplished by the use of a cam or eccentric. Suppose we attach the end of the piston rod

of Fig. 228 to the shaft *S* of Fig. 231. As the piston moves to the right the length of the cylinder, point *E* on the shaft moves in the same direction a distance equal to the diam-

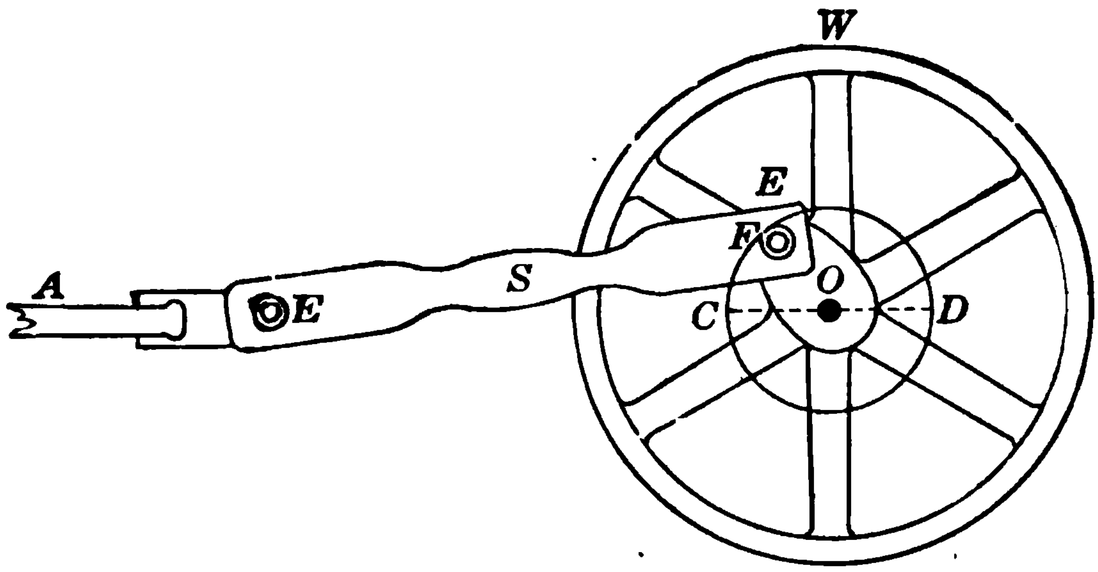



FIG. 231. — Reciprocating motion changed to rotary one by eccentric.

eter *CD*. Point *F* moves from *C* to *D* along the half-circumference. During the return stroke of the piston, *F* completes the revolution along the circumference, while *E* moves a distance equal to *DC*. The inertia of the heavy fly-wheel *W* carries the piston past the two points where there is no steam pressure, or past dead-center.

**259. How the Valves Are Controlled.** The slide valve *V* of Fig. 228 that alternately opens and closes the pipes leading from the steam chest to the cylinder is controlled by an eccentric. The rod *R* is coupled to the end of a shaft which is attached to the axis upon which the fly-wheel rotates. The diagram of Fig. 232 shows how the valve is controlled. The shaft *A* ends in a collar which fits around the disc *D*. This disc rotates about *C*, an axis which is off center. Let us follow the point *X*; during one half a revolution it moves along the curve as indicated by the arrows, but the end of the shaft at *A* moves to the left by a distance equal to

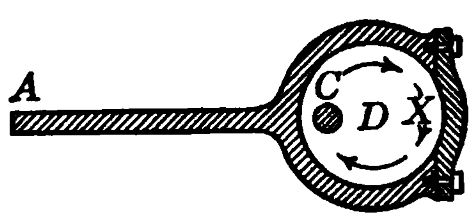



FIG. 232. — Valve controlled by cam or eccentric.

twice that of $CX$. As the revolution is completed the end of the shaft moves to the right an equal distance. While $X$ describes a complete circle, point $A$ moves to and fro, at the same time controlling the movement of the valve. Contrast with the method of controlling the valves on a locomotive, Fig. 229.

Corliss valves are used in many large steam engines. These valves open and close by turning slightly in the valve seats, Fig. 230. Each of the four valves may be timed independently of the others; greater efficiency can be obtained by using Corliss valves than by the use of the slide valve.

**260. The Steam Turbine.** The steam turbine works on the same principle as the water turbine, or the common windmill. In the Curtis turbine the steam is directed through nozzles against curved blades, as shown in Fig. 233. The principle is the same as that of the Pelton water-wheel. From the first set of movable blades the steam passes to a set of fixed blades, Fig. 234. It is then directed at an angle of high efficiency against another set of movable blades. In this manner it continues until its expansive force is practically spent.

FIG. 233 — Principle of turbine.

The Parsons and Westinghouse turbines consist of a cylindrical drum or rotor having a large number of blades set much like those of a windmill, Fig. 236, and a casing upon the inner side of which there are a large number of fixed blades, Fig. 235. The steam enters near one end of the

turbine and flows along the space between the rotor and the casing. As the pressure is thus reduced, the steam expands. The diameters of both the rotor and casing are made larger near the outlet end. The blades are also gradually increased in length. Fig. 237 shows the Westinghouse rotor with nozzle and reversing chamber.

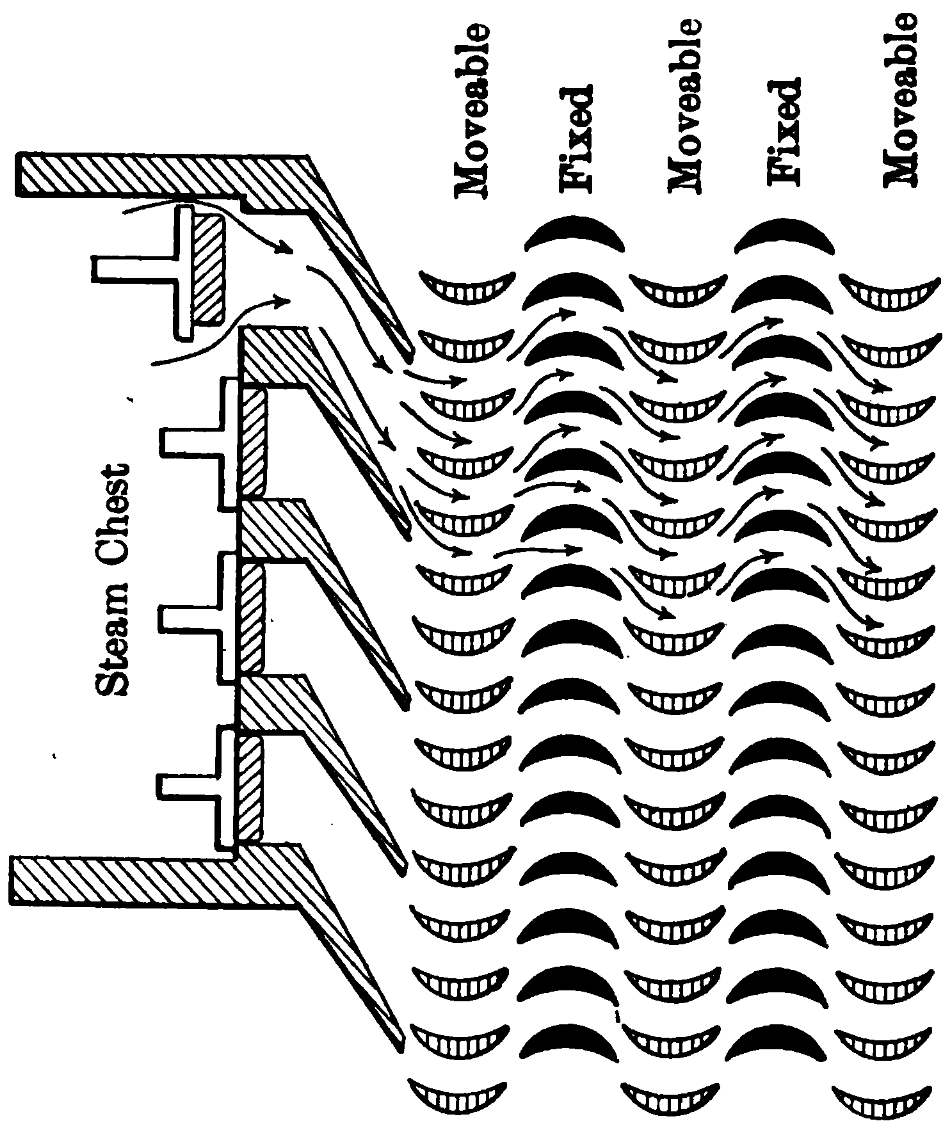


FIG. 234. — Path of steam through Curtis turbine.

**261. Advantages and Disadvantages of Turbines.** Turbines are extensively used on large ocean liners and destroyers, especially when high speed is desirable. For a given horse power, they occupy much less space than the reciprocating engine. The to-and-fro motion of the piston of a reciprocating engine causes a great deal of vibration, while a steam turbine runs more steadily. The turbine is also more efficient when working at a maximum capacity. It does not work well at a low speed. The chief disadvantage of the turbine arises from the fact that the direction cannot be reversed.

**262. The Gas Engine.** The gas engine is an internal-combustion engine. Some vapor, usually from gasoline, benzol, or alcohol, is mixed with air and the mixture exploded in the cylinder by an electric spark. The action of the four-

The inertia of the heavy fly-wheel keeps the piston moving during the other three cycles. The opening and closing of the valves, as well as the timing of the electric spark, are all controlled by cams or eccentrics. To make a gas engine run more steadily, several cylinders are grouped and so arranged that the explosions will be consecutive.

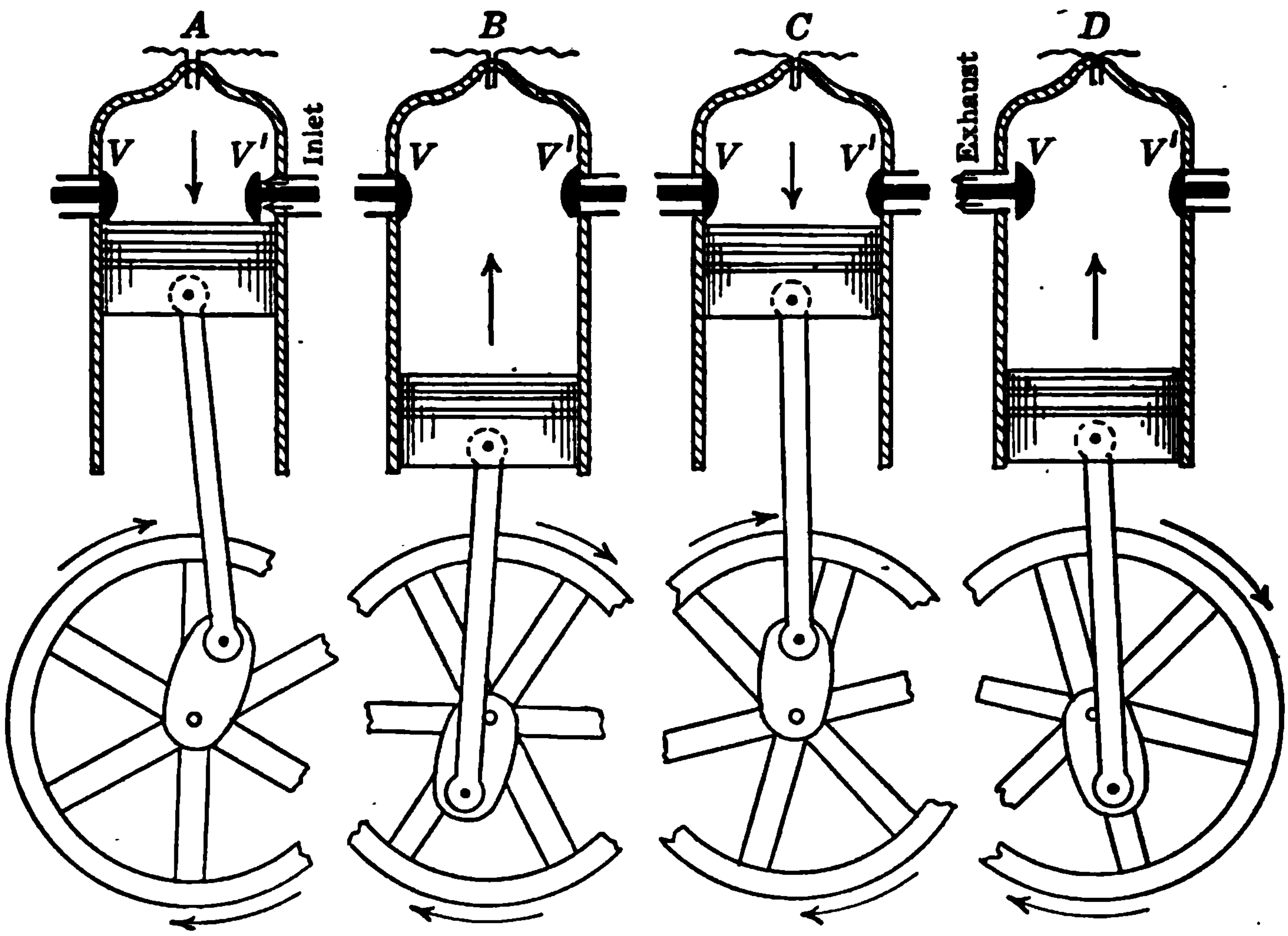



FIG. 238. — Four-cycle gas engine. *A*. Intake. *B*. Compression. *C*. Ignition. *D*. Exhaust.

**263. Two-cycle Engine.** We have seen that the working stroke of a four-cycle gas engine comes once in two complete revolutions. With the two-cycle engine there is a working stroke every revolution. The crank shaft of this engine revolves in a gas-tight crank case. On the upstroke of the piston *P* a partial vacuum is produced in this air-tight case. See Fig. 239. An explosive mixture of gas and air is then drawn in through *O* as the valve *V* opens. During the down stroke of the piston this mixture is compressed. When the piston reaches the point *A* the ports at *A* and *E* are both open. The waste gases from the preceding explosion pass

out at *E*, while the mixture which was compressed in the crank case flows through the by-pass and enters the cylinder at *A*. The next upstroke of the piston further compresses the gaseous mixture. The explosion occurs when the piston is near the top of the cylinder and the piston is driven downward during the working stroke.

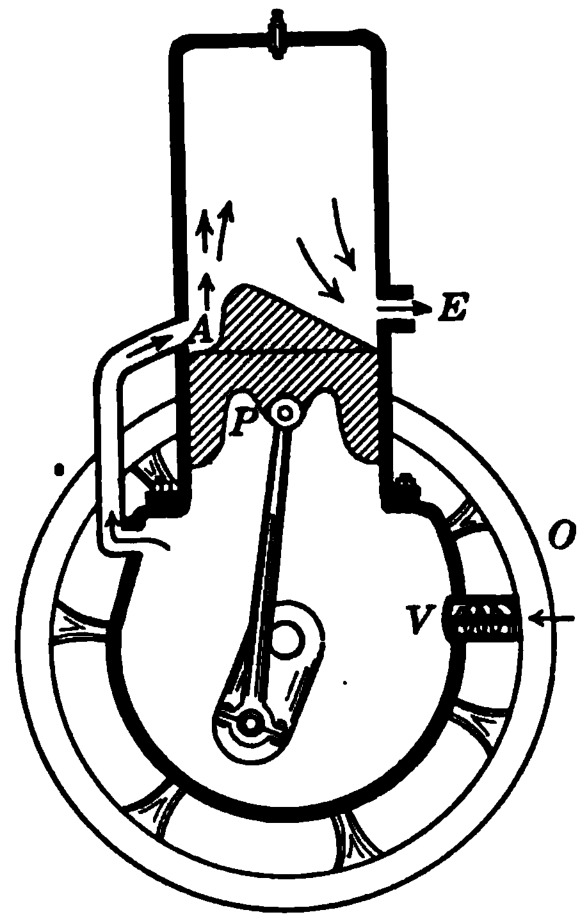


FIG. 239. — Two-cycle gas engine.

The student will observe that the tightly fitting piston takes the place of valves as it closes the intake and exhaust ports. The incoming gas is deflected upward to prevent its mixing with the exhaust gases. The absence of valves and valve mechanisms simplifies construction and makes the two-cycle engine cheaper to build than the four-cycle engine. It is not quite so efficient, however, since some of the unburned gases are lost through the exhaust. Two-cycle engines find use in motor cycles, and for the operation of motor boats.

**264. Diesel and Semi-Diesel Engines.** Diesel engines were designed to use oils heavier and cheaper than gasoline. The compression of the mixture is carried further than with the gasoline engine, and the temperature thus produced rises high enough to enkindle the oil vapors. During the first cycle of a four-cycle Diesel engine pure air is drawn into the cylinder. The piston on its return stroke compresses this air to a pressure of more than 30 atmospheres. Just before the beginning of the third cycle, the fuel valve opens to admit the oil vapors, which are forced into the cylinder by an air-blast of high compression. The vapors of the fuel

oil are automatically ignited as they meet the red-hot compressed air in the cylinder. This is the power stroke of the engine. The waste gases are removed during the fourth cycle just as with the gasoline engine. No ignition system is necessary.

In the *semi-Diesel* engines the compression used is not quite so great. A firing pin is heated red hot and screwed into the end of the firing chamber in order to start these engines. In the four-cycle engine air is admitted during

FIG. 240. — Semi-Diesel engine.

the first stroke and compressed during the second stroke of the piston. Before the compression stroke is completed, the fuel oil is forced into the explosion head of the cylinder, where it vaporizes instantly as it strikes the heated walls. Water is often introduced to prevent premature explosion before the maximum compression is produced. In other respects this engine does not differ from the Diesel types.

Two-cycle engines of the Diesel and semi-Diesel types are in use. Excepting the automatic ignition, they are not very different from the two-cycle gasoline engines. Additional mechanism must be used to deliver the fuel under high pressure. In the two-cycle engine, Fig. 240, the oil is forced

into the cylinder at $A$ under a pressure of 2600 lb. per sq. in. The oil is vaporized as it strikes the hot firing plug $P$.

**265. Advantages and Disadvantages of the Gas Engine.** The efficiency of the gas engine is about 25%, considerably

FIG. 241. — Liberty motor. This motor was developed by American engineers during the World War It was used for the heavy bombing planes. The twelve cylinders are water cooled. At 1700 revolutions per minute, the motor develops 400 horse power. Since its weight is just over 800 lb., it yields 1 H. P. for 2 lb. of its weight.

higher than that of the steam engine. It is very compact and furnishes a high horse power for its size. The new Liberty motor furnishes about 1 H.P. for 2 lb. of weight,

Fig. 241. The fuel takes up very little room, but it is quite expensive. Without the development of the gas engine the airplane would have been quite impossible. The gas engine may be started at a moment's notice, and it does not waste fuel when it is stopped. With the steam engine considerable time is required to produce steam, there is the trouble of stoking, and some fuel is always wasted when the engine is shut down.

The gas engine is very sensitive. The spark must occur at just the right time. With a steam engine the speed may be varied at will by regulating the amount of steam entering the cylinder; it can also be readily reversed. The gas engine cannot be reversed. While the speed can be regulated to some extent by advancing or retarding the spark, or by controlling the gas supply, yet gears are necessary to secure the proper variation of speed. The gas engine cannot be run economically at low speeds. The gas engine is often noisy and the gases from the exhaust are disagreeable and poisonous.

## SUMMARY

427 gm. meters of work are equivalent to one calorie of heat. One B.T.U. is equivalent to 778 ft. lb. of work.

Since heat may produce steam, and expanding steam produces pressure, the formation of steam furnishes one of the best methods of converting heat energy into work. The explosion of gasoline vapor is also much used for this purpose.

The ordinary steam engine uses from 7 to 20% of the total fuel energy. The gas engine is somewhat more efficient. The cam is used to change a reciprocating motion into a rotary one, and vice versa.

## QUESTIONS AND PROBLEMS

1. Why is ocean water unsatisfactory for use in steam boilers?
2. In steam boilers the flame is sometimes sucked through tubes

or flues surrounded by water. What advantage has such an arrangement?

**3.** A sled is drawn over the ice by a pull of 50 lb. How many B.T.U.'s will be produced by friction if the sled is drawn 10,000 ft.?

**4.** From what height must a block of ice fall to be melted by the heat of impact, assuming that 50 % of the heat generated is absorbed by the ice?

**5.** Why is the temperature of the steam in a pressure boiler more than 100° C.?

**6.** The average pressure of steam in an engine is 140 lb. per sq. in.; the diameter of the piston is 12 in. and the stroke is 24 in. How many ft. lb. of work are done at each stroke? at each revolution of the fly-wheel? If the fly-wheel makes 100 revolutions per minute, what is the horse power?

**7.** From a consideration of problem 6, what factors affect the horse power of an engine?

**8.** Would you expect the steam leaving the cylinder of a steam engine to have the same temperature as the steam which enters the cylinder? Explain.

**9.** How many B.T.U.'s of heat energy does a 175-lb. man lose in climbing a mountain 2000 ft. high?

## CHAPTER 14

# SOUND

### A. SOUND AND WAVE MOTION

**266. Source and Nature of Sound.** The origin of sound is some vibrating body. When matter is thrown into vibration, as in plucking a stretched string, striking a piece of metal, or firing a gun, sound waves are produced. See Fig. 242. Through some medium, usually air, these waves travel to the ear and so affect the auditory nerve that the sensation of sound is produced. In the *physiological* sense of the term, three things are essential for the production of sound: There must be a vibrating body; some medium for the transmission of the waves produced; and the ear, which serves as a receiver. In the *physical* use of the term, the word *sound* is synonymous with *sound wave.*

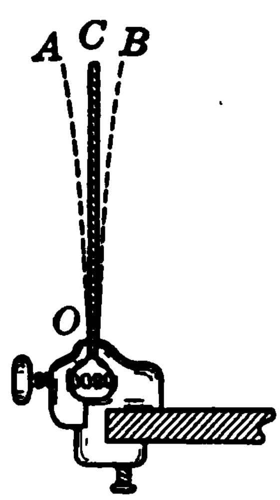


FIG. 242. — Vibrating body.

**267. Media for Sound Transmission.** When some one in the basement taps on a steam-pipe, the sound can be heard in all parts of the house. This shows that the metal pipe transmits sound readily. A street-car can be heard at a considerable distance when one is standing near a trolley pole, since the sound readily travels through the trolley wire. Some persons who are partially deaf can tune a violin perfectly; since the chin rests on the instrument, the vibrations are transmitted through the jaw-bone. A famous inventor, who is hard of hearing, is said to hear phonograph records

perfectly by resting his head against the cabinet of the instrument so the vibrations may travel through the bones of the head. In general, solids are better media for transmitting sound than liquids or gases. Such *porous* solids as sawdust, flannel, or cotton batting are poor transmitters. Material of this kind is used on floors and tables to deaden sound.

Liquids are better media than gases for sound transmission. If the ear is held under water, the paddle-wheels of a steamer can be heard a long distance. Fish are believed by fishermen to have very sensitive ears. It is quite doubtful, however, if they hear many sounds coming from the air, such as ordinary conversation between two persons. They doubtless hear clearly sounds that have their origin in the water itself.

Experience teaches us that gases, air for example, transmit sounds, although they are not as good media as solids and liquids. As the density of the air decreases, sounds become fainter. Since rarefied gases do not transmit sounds so well as dense gases, we are led to believe that sound would not travel through a vacuum. This conclusion may be verified by putting a small alarm clock under a bell-glass and exhausting the air. If the clock is supported on layers of felt or other non-conducting material, so the vibrations will not travel through the base of the pump, the sound will gradually grow fainter as we pump the air out of the bell-glass, finally becoming almost inaudible when a good vacuum has been obtained.

**268. Velocity of Sound in Air.** We often hear a thunderclap several seconds after the lightning flash. When a pistol is fired at a distance of several hundred feet, we see the flash a few seconds before we hear the report. The interval is the time required for the sound to travel the intervening distance, since for short distances light is practically instantaneous. The velocity of sound was determined by setting up cannon on hills several miles apart and firing them alter-

nately. The distance was carefully measured, and the time required for the sound to travel that distance was carefully reckoned. By firing from the different positions, the errors due to the velocity of the wind were eliminated. The average of a large number of trials by these direct methods and also by indirect methods which have been used shows that *in air at 0° C. the velocity of sound is 1090 ft. per second.* As the temperature rises the velocity increases. The rate of increase is about *2 ft. per second for 1° C.* In the Metric System the velocity at 0° C. is 332 meters; the increase in velocity per degree is about 0.6 meter.

**269. Velocity of Sound in Other Media.** The velocity of sound in many other media has also been determined. In water it is approximately four times as great as in air. In steel it is more than 15 times as great. The velocity in any medium is inversely proportional to the square root of the density, but it is directly proportional to the square root of the elasticity. Elasticity is used here in the same sense that it was used in § 87. The velocity of sound is very high in solids, on account of their high coefficient of elasticity. The velocity in any solid may be calculated from the formula,

$$V = \sqrt{\frac{\text{elasticity}}{\text{density}}}.$$

**270. Vibration.** If a steel strip is clamped at one end and struck a sharp blow with a hammer at its free end, it vibrates or moves to and fro, as shown in Fig. 242. Just as in the vibration of the pendulum, the movement from $A$ to $B$ constitutes a *single* vibration; from $A$ to $B$ and return is a *complete* vibration. The *amplitude* of vibration is the angle $AOC$; the *period* is the time required for one complete vibration; and the *frequency* is the number of vibrations per second.

**271. Kinds of Vibrations.** Vibrations may be transverse or longitudinal. Water waves are *transverse* to the

line of propagation. There is little or no forward movement of the water itself, but a rising and falling motion as the wave advances. See Fig. 243. That there is no progressive

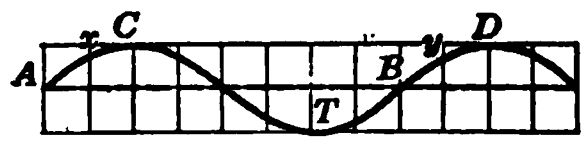



FIG. 243. — Transverse waves.

motion in transverse waves is well illustrated by a field of waving grain. Before the wind the stalks bend forward and downward; after the wind has passed, they bend upward and backward. The wave travels across the field, but of course there is no progressive movement of the grain itself. If a spiral spring several feet long, as in Fig. 244 *A*, is plucked at right angles to its length, a transverse wave is set up which travels along the coil to the other end, and is then returned by reflection.

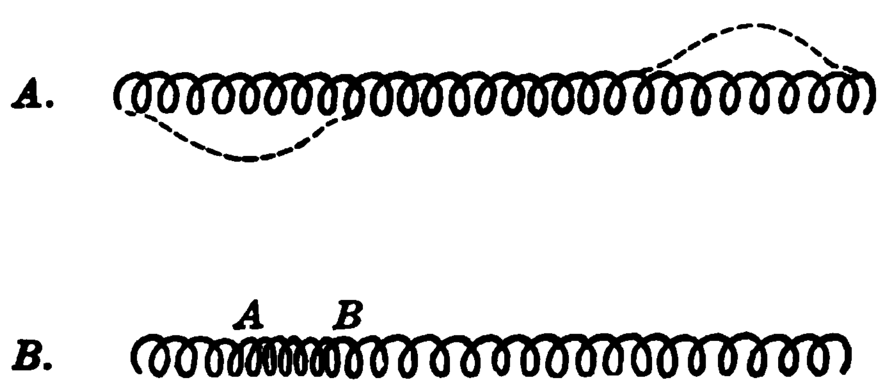



FIG. 244. — *A*. Transverse waves. *B*. Longitudinal waves.

If we compress several turns of the coil, Fig. 244 *B*, and then release it quickly, a wave is produced that vibrates in the same direction as the path along which it travels. Such a vibration is *longitudinal.*

**272. Sound Waves Are Longitudinal.** While the steel strip of Fig. 242 is moving from *A* to *B*, the air immediately in front is compressed. While the strip then moves from *B* to *A*, a slight expansion of the air occurs. In this way a series of *condensations* and *rarefactions* is produced. The crowded lines of Fig. 245 represent the condensations and


FIG. 245. — Train of waves.

the others the rarefactions. The train of waves is longitudinal, taking place in the direction of propagation. There is little forward movement of air, each pulse communicating its energy to the air in front in much the same manner as with the collision balls of Fig. 246. If ball $A$ is raised and then let fall, the impulse is communicated to each ball in turn, until $C$ is reached. This ball then flies out to the position shown, the others remaining stationary.

FIG. 246. — How waves progress.

The length of a water wave is measured from a particle in one wave to a particle in the same phase of the next wave. See Fig. 243. The length may be measured from $A$ to $B$, from $C$ to $D$, or from $X$ to $Y$. The highest parts of the waves as shown at $C$ and $D$ are called the *crests;* $T$ is the *trough* of the wave. Sound waves are measured from condensation to condensation, $A'$ to $B'$, or from rarefaction to rarefaction, $C'$ to $D'$, in Fig. 245.

**273. Relation between Velocity, Wave Length, and Vibration Rate.** If the velocity of sound in air is 1100 ft. per second, and a fork is vibrating 275 times per second, it is evident that the first sound wave will have traveled 4 ft. before the next one is produced ($1100 \div 275 = 4$); before the third vibration has started, the first sound wave will be 8 ft. distant and so on; by the time the 275th vibration is produced at the end of one second, the first wave will be 1100 ft. distant. The algebraic expression for this relationship is $v = nl$, in which $v$ is the velocity of sound per second, $l$ the wave length, and $n$ the frequency, or the number of vibrations per second. If any two of these quantities are known, the third may be easily determined.

**274. Reflection of Sound.** Just as a rubber ball rebounds from a hard surface, so sound waves are reflected from a

cliff or forest. The sound wave strikes a medium of greater density and is turned back. A sounding board is sometimes placed back of a speaker to reflect the sound waves to the audience. *An echo is a repetition of a sound due to the reflection of the sound wave from some surface.* The reflected wave travels at the same velocity as the direct wave. On a day when the temperature is 20° C., the velocity of sound is 1130 ft. per second. A cliff 1130 ft. distant will produce an echo after 2 seconds. Several echoes may be produced in succession by parallel walls. The rolling of the thunder is caused by echoing and reëchoing as the sound wave is reflected from cloud to cloud, or from a cloud to the earth.

**275. Acoustic Properties of Buildings.** In large halls or assembly rooms, echoes sometimes make it quite impossible to understand the speaker. Suppose the velocity of sound is 1120 ft. per second. If a speaker utters a word every half second in a room 280 ft. long, the echo from the first word will be returned just as the second word is spoken. If a syllable is spoken every quarter of a second, a wall 140 ft. away will produce the same effect. The duration of sound is $\frac{1}{10}$ of a second. This means that the sensation of sound continues for $\frac{1}{10}$ of a second after the sound stops. Confusion will result if an echo returns before the original sound dies out. It is a well-known fact that halls about 55 ft. long are difficult for speakers because the echoes are so troublesome. In such cases the echo returns before the sensation from the original sound has disappeared. A trained speaker will so time his words and syllables that the echo does not produce confusion. In small rooms echoes are not noticeable. Furniture and draperies are often helpful in breaking up the sound wave so that it is not reflected as a single wave. Very often the echoes in a large room nearly disappear when the room is filled with people. The construction of buildings that have good acoustic properties is an art in itself. Dome-shaped ceilings often make the rooms whis-

pering galleries. In the Capitol building at Washington persons on one side of the Hall of Statuary can hear distinctly whispers uttered near the opposite side, although they are inaudible to persons in the center of the room, only half as far away. A low whisper uttered near one side of St. Paul's Cathedral in London is distinctly audible at the other side, over 100 ft. away.

**276. The Speaking Tube.** Ordinarily sound waves spread out in all directions from the vibrating body. If one speaks into the end of a tube, however, the sound wave cannot spread out over so large an area, but it is intensified in one direction. The speaking tube is used quite extensively in apartment houses, and as a means of communication between the different floors of certain buildings.

The *megaphone* and the *graphophone horn* are similar to the speaking tube in principle, both having a tendency to localize sound waves and transmit them in one general direction. In the *ear trumpet* the principle of the megaphone is reversed. See Fig. 247. The larger end receives more of the sound wave and thus augments the sound by reflecting a larger volume of the sound wave to the ear. The *stethoscope* used by physicians is similar in principle to the ear trumpet.

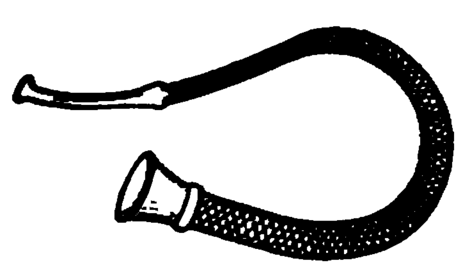


FIG. 247. — Ear trumpet.

**277. Sound Waves Photographed.** By means of actual photographs the behavior of sound waves has been studied. The photographs reproduced on the opposite page, Fig. 248, were taken by Professor A. L. Foley of Indiana University. The sound wave was produced by means of a spark between electric terminals. The sound wave spreads out in all directions, forming larger and larger spheres as it advances. As it strikes a plane surface through which it cannot pass, the wave is bent back upon itself. From curved surfaces it is also reflected, but its curvature is increased as it is turned

*A* *B*

*C* *D*

*E* *F*

Fig 248. — Photographs of sound waves taken by Professor A. L. Foley of Indiana University. *A*. Spherical sound wave taken 0.0001 sec. after the spark that produced the wave. *B*. Sound wave taken 0.00015 sec. after spark. Shows expanding wave and reflection from convex surface of a gas lens. *C*. Same wave 0.00023 sec. after spark. Shows original wave, reflected portion, and plane wave transmitted through gas lens. *D*. Spherical wave reflected from plane mirror. *E*. Sound wave reflected from parabolic mirror. Reflected wave is plane. *F*. Reflector is sheet of tin with four rectangular openings. Waves are reflected from five sections of tin, which have become new centers of disturbance. The waves passing through the openings are diffracted.

back from a convex surface, and decreased as it is reflected from a concave surface. Sound waves are refracted, or bent out of their course, in passing through a lens filled with some gas that is denser than air. After passing through such a lens in *C* the wave is nearly plane.

## *B.* LOUDNESS AND PITCH

**278. Sound Characteristics.** Some sounds are loud, others are soft and low; the chirp of a cricket is a very shrill note, while the growl of a bull-dog is a deep bass; we enjoy hearing some persons sing, but unfortunately some other voices are not so pleasing. Sounds differ in three ways: (1) in *loudness*, or *intensity;* (2) in *pitch;* and (3) in *quality.*

**279. Intensity and Loudness.** The intensity of sound depends upon the sound waves themselves, while loudness depends upon the effect they produce on the auditory nerves. The *intensity* is dependent upon two factors; the *amplitude*, and the *area* of the vibrating body. When a string is lightly bowed, only a small amount of energy is imparted to the surrounding medium and the sound is a faint one. More vigorous bowing increases the amplitude and the sound becomes more intense.

A large tuning fork produces a much greater volume of sound waves than a small fork, hence the sound carries farther. When a small vibrating fork is placed on the table it sounds much louder. The table is forced into vibration, thus increasing the area of the vibrating body.

*Loudness depends upon the nature of the conducting medium and also upon the distance.* We have already learned that certain media transmit sounds better than others. Since sound waves are given off in all directions, the more distant waves will spread out over a greater area, as in concentric spheres. Since the surfaces of concentric spheres have areas proportional to the squares of their radii, the *loudness of a*

*sound is inversely proportional to the square of the distance from the source.*

**280. Pitch.** By using a rotator and a siren disc like that of Fig. 249, it may be shown that the pitch rises as the frequency increases. The disc shown has four rows of holes, numbering 24, 30, 36, and 48 respectively, all regularly spaced. The holes in the fifth row are irregularly spaced. If a stream of air is directed against the inner row of regularly spaced holes while the disc is rotated, the pitch of the sound will rise as the speed of rotation is increased. If the speed is kept uniform and the stream of air is directed against the rows having more holes, the pitch rises even more. The number of air-pulses, or vibrations per second, equals the number of holes times the number of revolutions per second. This experiment proves quite conclusively that *the pitch of a tone depends upon the number of vibrations that reach the ear per second.* Since the velocity of sound equals the frequency times the wave length, it is evident that the pitch rises as the wave length decreases, or as the frequency increases. The wave length of a fork vibrating 256 times per second is just twice that of a fork vibrating 512 times per second. The pitch of the latter is higher than that of the former, since twice as many sound waves reach the ear per second.

FIG. 249. — Siren disc.

If the stream of air is directed against the irregularly spaced holes of the siren disc, the vibrations are irregular and a jarring noise is produced. This is one of the distinctions between noise and music; in music, the pulses reach the ear in regular succession.

**281. Doppler's Principle.** When the distance between

the ear and a vibrating body is constant, the number of pulses reaching the ear per second is exactly equal to the frequency. If a train approaches one very rapidly, a larger number of pulses reaches the ear per second. The pitch of the whistle rises, falling again as the engine recedes. Suppose the whistle sends out 300 pulses per second, and the velocity of sound is 1140 ft. per sec. The length of the sound wave is 3.8 ft. Now if the train has a velocity of 45 mi. per hr., or 66 ft. per sec., it will be 17.3 wave lengths nearer the listener at the end of one second. Therefore 17.3 more pulses reach the ear per second, giving a pitch corresponding to 317.3 vibrations per second instead of 300. As the train recedes, 17.3 pulses are subtracted from the normal vibration rate, and the pitch falls to 282.7 vibrations per second. Such a rise in pitch when a sounding body approaches, or fall in pitch when it recedes, is known as Doppler's principle.

## *C.* RESONANCE AND INTERFERENCE

**282. Forced Vibrations.** A tuning fork vibrating freely has a natural vibration rate. The strings of musical instruments have a vibration rate free from external influences except gravity and friction. We know that a tuning fork may impress its vibration rate upon a table upon which it is placed. Energy is transmitted through the stem of the fork, and the table is forced to vibrate in response to the periodic force thus applied. When a string is stretched over the body of a violin, the thin wood of which the violin is composed is forced to vibrate in response to the vibrations of the string. The sounding board of a piano is another example of forced vibration. In all these cases the intensity of the sound is increased.

**283. Sympathetic Vibrations.** Suppose we have given two mounted tuning forks, Fig. 250, both having the same

vibration rate. Let us start one fork to vibrating and after a few moments check it completely. It is now possible to hear the other fork which is vibrating sympathetically. The impact of the sound waves from the first fork falling in regular succession upon the second fork has thrown it into *sympathetic vibration.* The strings of a violin may be heard vibrating softly when a person playing a piano in the same room strikes the notes which have the same pitch as the violin strings. Sympathetic vibrations occur when the vibration rates are the same, or when one is an even multiple of the other. If we weight the prongs of one tuning fork and repeat the experiment, the second fork does not vibrate sympathetically with the first, because their vibration rates are now different.

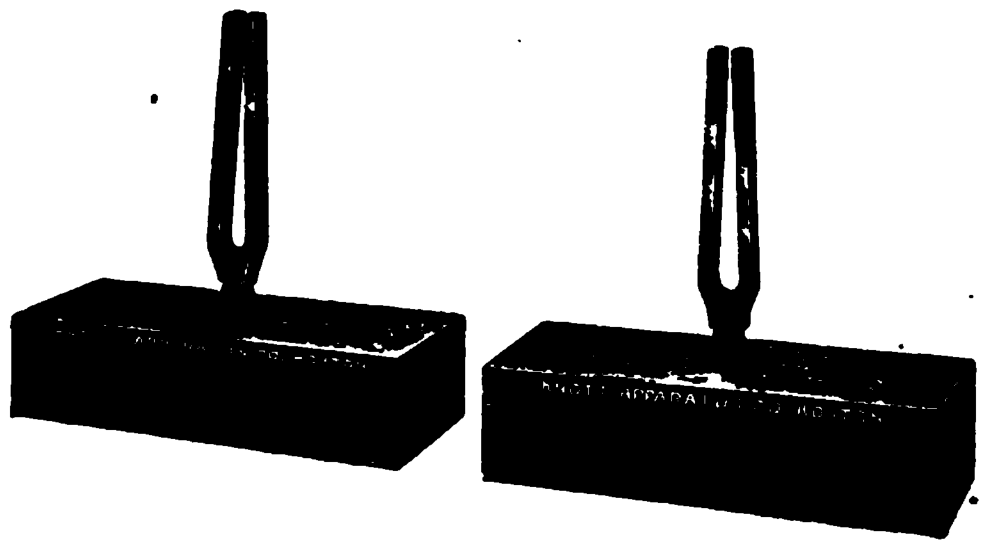


FIG. 250. — Resonant forks.

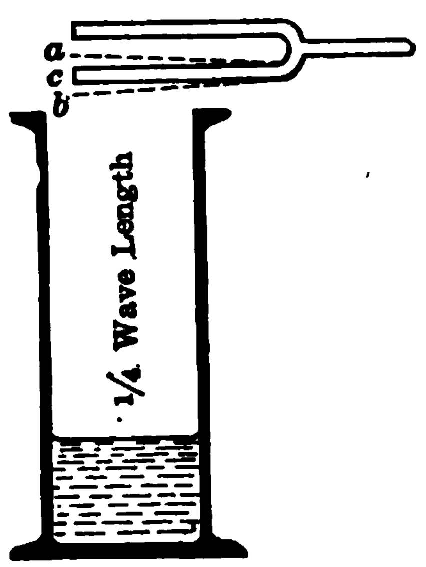



FIG. 251. — Resonance by closed tube.

**284. Resonance.** Let us hold a vibrating tuning fork over a cylinder partially filled with water. By pouring water into the cylinder gradually, it is possible to find a point where the sound wave reflected back from the water surface unites with the direct wave from the fork and reinforces the sound. A tube so adjusted that the air column inside vibrates in unison with a fork or other outside body is called a *resonator*. See Fig. 251. Suppose the prong $C$ moves from $A$ to $B$ and back in making a complete vibration. In order to produce

resonance, the sound wave must travel down the tube and back while $C$ is making a *single* vibration. Then while $C$ makes a *complete* vibration, the wave will travel four times the length of the tube. If the reflected wave returns so that a condensation meets a condensation, the sound is reinforced. *Resonance may be defined as the reinforcement of sound by the union of the direct and reflected sound waves. A closed tube whose length is one fourth the wave length of the fork produces the best possible resonance.* Resonance is also produced when the tube is $\frac{3}{4}$, $\frac{5}{4}$, $\frac{7}{4}$, etc., of the wave length.

When a vibrating fork is held over an *open* tube, resonance is produced. The sound wave spreads out when it reaches the lower end of the tube and a condensation is returned as a rarefaction. With an *open* tube, experiment shows that the best resonant length is *one half* the wave length.

**285. Interference.** Suppose we continue the experiment described in the preceding section by pouring water into the cylinder until the air column is $\frac{1}{8}$ the wave length of the fork. When the reflected wave meets the direct wave in this case, a condensation will meet a rarefaction and the sound will be reduced or extinguished. Interference may also be produced when two sets of sound waves of unequal length traverse the same medium in one direction.

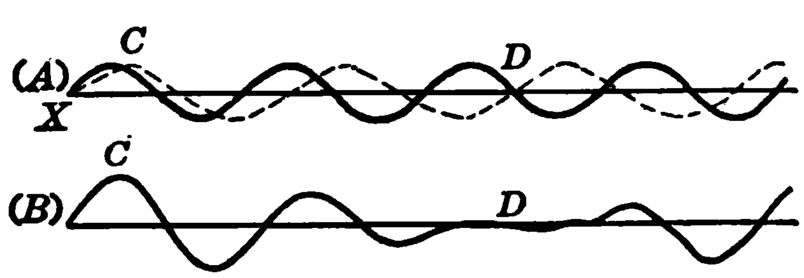


FIG. 252. — Interference.

It is easy to imagine that the crest of a water wave coinciding with the trough of another wave would fill the depression and tend to make the water surface level. In Fig. 252 we see how interference occurs. Suppose the heavy line in ($A$) represents a sound wave four feet long, and the dotted line a sound wave five feet long, both starting from the point $X$. In ($B$) we have a composite curve constructed

by using the resultant of the crests and troughs of the two trains of waves. At $C$ the crests which represent condensations meet and the sound is intensified; at $D$ a condensation is coincident with a rarefaction, and the sound is diminished, or silence may result. *An outburst of sound followed by an interval of comparative silence is called a beat.* The number of beats per second is equal to the difference in the vibration rates of the two vibrating bodies. For example, a tuning fork whose frequency is 256 will produce 4 beats per second when sounded with a fork whose vibration rate is 260, or with one whose frequency is 252.

## SUMMARY

Sound has its origin in a vibrating body. Sound waves are transmitted to the ear through some medium. Solids are the best media for sound transmission; liquids and gases follow in the order named. Sounds do not travel through a vacuum.

The velocity of sound in air at 0° C. is 1090 ft. per sec. The velocity increases 2 ft. for a rise in temperature of 1° C.

Sound waves may be reflected, producing echoes. When the reflected sound wave reinforces the direct wave, resonance is produced. The best resonant length for a closed pipe is $\frac{1}{4}$ the wave length; the best resonant length for an open pipe is $\frac{1}{2}$ the wave length. Parallel walls often produce multiple echoes.

When two sound waves are so superimposed that a condensation meets a rarefaction, the sound is reduced by interference. An outburst of sound followed by an interval of comparative silence is termed a beat.

Sounds differ in loudness, pitch, and quality. Pitch depends only upon the number of vibrations that reach the ear per second. Loudness depends upon the amplitude of vibration, the area of the vibrating body, and the distance from the source of sound.

## QUESTIONS AND PROBLEMS

1. Do sounds of different pitch travel at the same velocity? Give a reason for your answer.

2. A fork that makes 384 vibrations per second produces reso-

nance with a closed tube 8.9 in. long. Find the velocity of sound. What is the approximate temperature?

3. A person standing near one end of a long iron pipe hears two distinct sounds when the other end of the pipe is struck with a hammer. Explain.

4. Why does the pitch of a circular saw fall as a board is pushed into the saw?

5. At a track-meet should the timers start their stop-watches with the flash of the pistol or its report? Give a reason for your answer.

6. A man counts 12 sec. between a flash of lightning and the thunder crash when the temperature is 22° C. How far away did the electrical discharge occur?

7. Why is it difficult for one speaking in the open air to be heard?

8. A man sets his watch by a whistle 2 mi. distant. If the temperature is 20° C., how much will his watch be in error? Will it be too fast or too slow? If the wind is blowing with a velocity of 30 ft. per sec., how will the result be affected?

9. Three seconds elapse between the firing of a gun and the return of the report. How far away is the reflecting surface?

10. When the temperature is 20° C., a fork vibrates 51 times per second. What is the wave length produced?

11. How can echoes be of use to vessels at sea in a heavy fog?

12. How do you account for the peculiar shape of the ceilings in the railroad stations of some cities?

13. A closed tube is 30 cm. long. It produces resonance with a tuning fork when the temperature is 25° C. What is the wave length of the sound reinforced? What is the frequency of the fork?

14. Why was it so difficult to cut the barbed-wire entanglements in "no man's land" without being heard by the enemy?

15. Why is it difficult for the men in the rear of a long line of soldiers to keep in time with a band in front?

16. A little dog trotting across a bridge causes it to vibrate more vigorously than a team of horses drawing a heavy load. Explain.

17. Why are soldiers commanded to break step when crossing a long bridge?

18. Deaf children listen to music by resting their hands and heads upon the frame of a piano. Explain.

## CHAPTER 15

# SOUND — MUSIC

### *A.* MUSIC AND QUALITY

**286. Diatonic Scale.** Suppose we repeat the experiment in which the siren was used, this time forcing air through the four rows of holes at the same time; the four notes sounding together produce a *major chord.* The vibration ratios of the notes emitted will be the same as the number of holes, 24, 30, 36, and 48; the simplest ratio is 4, 5, 6, and 8. Any three notes whose vibration ratios correspond to 4, 5, and 6 produce a *major triad* when struck simultaneously; these three notes with the octave above the first note produce a major chord. *The major diatonic scale is built up of three major chords,* as the accompanying table shows:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Syllables . . . . | do | re | mi | fa | sol | la | si | do | re |
| Letters . . . . . | C | D | E | F | G | A | B | C′ | D′ |
| Vibration rates . . | 256 | 288 | 320 | 341 | 384 | 426 | 480 | 512 | 576 |
| Relative vibration rates | 24 | 27 | 30 | 32 | 36 | 40 | 45 | 48 | 54 |
| Chord (tonic) . . . | 4 | | 5 | | 6 | | | 8 | |
| Chord (dominant) . | | | | | 4 | | 5 | | 6 |
| Chord (subdominant) . . . | | | | 4 | | 5 | | 6 | |

The note C′, which is just one *octave* above C, has a vibration rate just twice as great as that of C. From the relative vibration ratios we see that to produce D, an object must vibrate $\frac{9}{8}$ times as fast as it does to produce the note C; D is just $\frac{1}{2}$ of D′, being an octave lower; the vibration rate of E is $\frac{5}{4}$ that of C; F is $\frac{4}{3}$; G is $\frac{3}{2}$; A is $\frac{5}{3}$; and B is $\frac{15}{8}$. See

Fig. 253. In the second octave we see that D′ has a frequency just twice that of D; it is also just $\frac{9}{8}$ times that of C′, the key-note in the same octave. In the same manner we can find the frequency of any note in this octave by multiplying the vibration rate of the key-note by the ratios just given. For example, the frequency of E′. equals $\frac{5}{4}$ times 512 (C′), or 640.

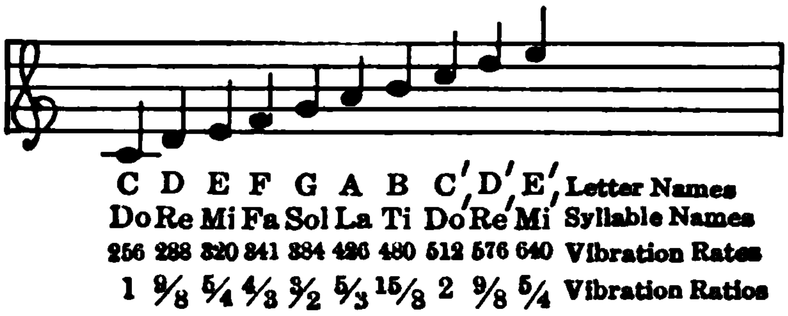



Fig. 253. — Major diatonic scale. Key of C.

**287. The Chromatic Scale.** Let us use D as the key-note and multiply its vibration rate by the ratios used in the preceding section. The results differ from those obtained in the key of C as follows:

| | C | D | E | F | G | A | B | C′ | D′ |
|---|---|---|---|---|---|---|---|---|---|
| Key of C . . . | 256 | 288 | 320 | 341 | 384 | 426 | 480 | 512 | 576 |
| Key of D . . . | | 288 | 324 | 360 | 384 | 432 | 480 | 540 | 576 |

We observe that there is considerable variation, especially in the vibration rates of F and C′. The difference is so great that two new notes, F# and C#, are used by the musician when he plays in the key of D. The vibration rate of F sharp, or F#, is obtained by multiplying the frequency of F by $\frac{25}{24}$; if a note in the chromatic scale is to be flatted, its frequency is $\frac{24}{25}$ that of the note itself. These intervals are called *chromatic semitones.* By using different letters as key-notes, we find that five new notes, called sharps or flats, must be added to each octave. The notes in the diatonic scale are represented by the white keys on the piano; the chromatic scale includes also the five chromatic semitones, which are represented on the piano or organ by the black keys.

**288. The Tempered Scale.** In building up the chromatic scale, we learned that five new notes must be added to the diatonic scale in each octave. If we examine the two scales shown above, keys of C and D, we note that there is a difference of 4 vibrations for the note E and about 6 for the note A. If all the possible keys were built up in the same manner and new notes added where any difference exists, a large number of additions would be needed. The black keys on the piano are used either as the sharp of the note below or as the flat of the note above. In the diatonic scale there is a difference between C♯ and D♭. For example, $\frac{25}{24}$ times 256 equals 266 vibrations, or C♯; and $\frac{24}{25}$ of 288 equals 276 vibrations, or D♭. Putting in new notes with their sharps and flats wherever even slight variations occur would give an octave of about 70 notes. The difficulty in learning to play a piano or organ having 70 notes in each octave is obvious; it is so impractical that a system of equal

| Diatonic Scale | | Tempered Scale | |
|---|---|---|---|
| C | 256 | C | 256 |
| C♯ | 266.6 | C♯ or D♭ | 271.2 |
| D♭ | 276.5 | | |
| D | 288 | D | 287.3 |
| D♯ | 300 | D♯ or E♭ | 304.4 |
| E♭ | 307.2 | | |
| E | 320 | E | 322.5 |
| F | 341.3 | F | 341.7 |
| F♯ | 355.5 | F♯ or G♭ | 362 |
| G♭ | 368.6 | | |
| G | 384 | G | 383.6 |
| G♯ | 400 | G♯ or A♭ | 406.4 |
| A♭ | 409.5 | | |
| A | 426.6 | A | 430.5 |
| A♯ | 444.4 | A♯ or B♭ | 456.1 |
| B♭ | 460.8 | | |
| B | 480 | B | 483.3 |
| C′ | 512 | C′ | 512 |

FIG. 254. — Comparison of diatonic and tempered scales.

temperament has been devised. There are twelve *intervals* in the octave, including sharps and flats, and the vibration rate of C′ is just twice that of C. By extracting the twelfth root of 2, we get an equal interval for each semitone.

$$\sqrt[12]{2} = 1.05946.$$

In the tempered scale the vibration rate of any note can be obtained by multiplying the frequency of the preceding note by 1.05946. The equally tempered scale is used in playing most musical instruments. A skilful violinist, however, may produce better music by using the true intervals of the diatonic scale. A comparison of the two scales is shown in Fig. 254. The difference is not very great in any case. In fact few persons can tell a difference in pitch of only 2 or 3 vibrations per second.

**289. Standard Pitch.** The middle C tuning forks that are used in all physical laboratories are all tuned to 256 vibrations per second. This gives A 427 vibrations per second. In *concert* pitch, which is now little used, middle C has 271 vibrations per second. *International* pitch differs slightly from that used by physicists in the diatonic scale, since A equals 435 vibrations per second. With the pitch adopted by the American Federation of Musicians, A has 440 vibrations per second. Sopranos find it difficult to sing music written by Handel and his contemporaries when accompanied by instruments tuned to the pitch adopted by the American Federation of Musicians.



Fig. 255. — Beats produced by singing flames.

**290. Harmony and Discord.** Connect two jet tubes to the gas-cock. See Fig. 255. Support two glass tubes about 1 in. in diameter and 16 to 18 in. long over the jet tubes. Adjust the height of the flames properly and a singing noise will be produced. Now if the tubes are made

unequal in length by means of a sliding paper cylinder, beats will be produced. When there are only a few beats per second, the sound is not displeasing. It is possible so to adjust the lengths of the tubes that a jarring, discordant noise may be heard; this occurs when the number of beats increases to about 30 per second.

If two or more notes give a pleasing sound when they are sounded together, they are said to produce *harmony.* From the experiment we learn that the effect produced depends upon the number of beats per second. If the number of beats is 60 or more, they are so close together that the ear does not distinguish between them and harmony is produced. The *maximum discord* occurs when there are about 30 beats per second.

**291. Limits of Audibility.** If the number of vibrations is fewer than 16 per second, the waves set up do not affect the auditory nerve and no sound is heard. The vibration rate of the lowest note on a piano is 27. It is said that the ears of some persons are not sensitive to this note. A note of very low pitch may be produced by pressing the forefingers against the ear, and then closing the other fingers firmly. It is also true that the vibrations may become so rapid that the ear is not affected. The frequency at which this occurs varies with the individual, but the maximum vibration rate capable of being perceived by the ear appears to vary from 38,000 to 40,000 per second. The shrill chirp of the cricket is inaudible to some persons. The loudness has nothing to do with such cases. The auditory nerves of such persons do not seem to be tuned to receive notes of very high or very low pitch, just as some eyes are not sensitive to certain colors.

**292. Fundamentals and Overtones.** When a string vibrates as a whole, it yields a note of its lowest possible pitch. Such a note is called its *fundamental;* it is produced when a string, Fig. 256, is plucked or bowed near the middle. The

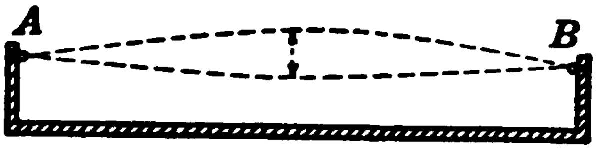



FIG. 256. — String vibrating as a whole sounds fundamental.

sonometer is an apparatus used in the laboratory for the study of vibrating strings. Suppose we divide a sonometer string into eight equal parts and put *V*-shaped paper riders on the string in the positions shown at 1, 2, 3, 4, and 5 of Fig. 257. If we touch the string at *C* and then bow it at *D*, the riders at positions 1, 3, and 5 will be thrown off. Those at 2 and 4 will not be disturbed. The experiment shows that the string is now vibrating in four parts, or segments. That portion of the string included between *A* and *B*, Fig. 258, is called a *loop* or *segment*. The points where no vibration occurs are called *nodes*.

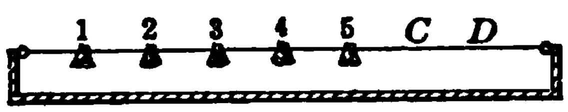



FIG. 257. — String vibrating in segments.

One of the most interesting things about this experiment arises from the fact that the pitch is increased until it is two octaves higher than the fundamental. *A note whose vibration rate is a multiple of that of the fundamental is called an overtone, or harmonic.* When a string vibrates in two segments, the first overtone is produced; its pitch is an octave above the fundamental. The second overtone has a frequency three times that of the fundamental; the second overtone of C is the note G′. The third overtone has a vibration rate four times that of the fundamental, and so on.

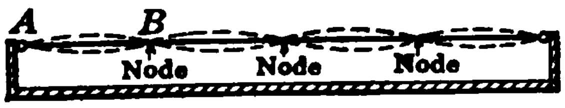



FIG. 258. — Loops and nodes.

**293. Quality.** It is easy to pick out the various instruments in an orchestra, although the pitch may be the same. Two persons may sing true to pitch and yet the voice of one may be the more pleasing. *The quality of a sound depends upon the number of overtones present and upon their prominence.* This difference in quality may be demonstrated by bowing a string near the middle. While it is vibrating as a whole and

sounding its fundamental, if we touch it *lightly* at the middle, it will still continue to vibrate, but it now vibrates as a whole and in two segments. See Fig. 259. In the second case the tone is richer and fuller. Its quality has been improved by the presence of the first overtone blended with the fundamental. When a string is plucked or bowed near one end, it always vibrates as a whole and in segments. The quality is better than when the string is plucked or bowed at the middle, since the sound is richer and fuller. Certain overtones are displeasing to the ear, since they produce notes that do not harmonize with the notes of the musical scale. For this reason a piano is so constructed that the hammers strike the strings about $\frac{1}{7}$ of their length from one end; this suppresses the sixth overtone, whose vibration rate produces a discord when sounded with certain notes of the musical scale.

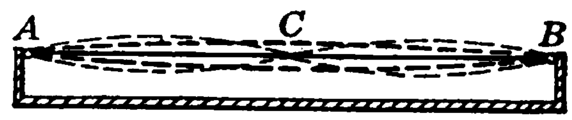



FIG. 259. — Overtones are produced by strings vibrating in parts.

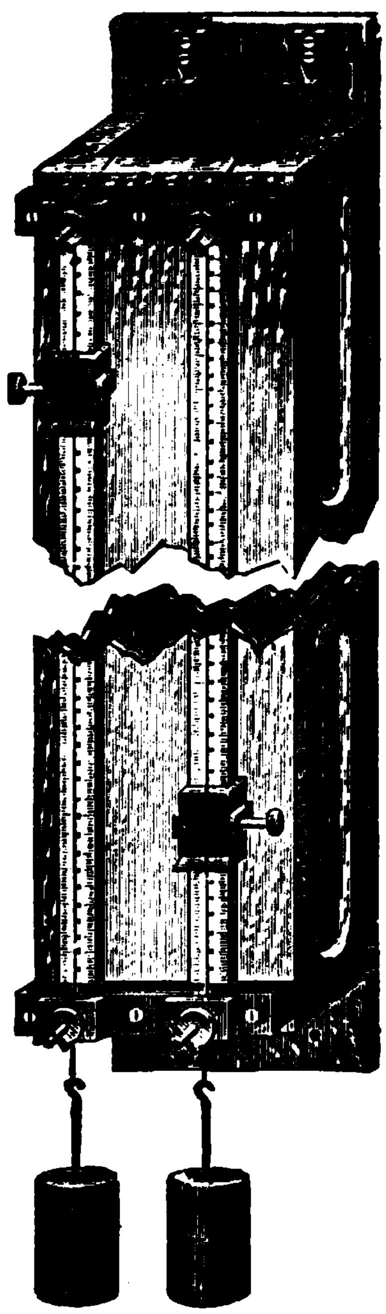


FIG. 260. — Sonometer.

**294. Laws Governing the Vibration of Strings.** If we examine a piano, we find that the bass strings are longer, thicker, and looser than those of the treble. Their density is also made greater by winding them with copper. In the construction of the piano we have examples of all the methods used to change the frequency of strings. By a careful study of the vibration rate of strings stretched over a sonometer (Fig. 260), several facts have been determined. The laws of strings may be stated as follows:

1. *Law of lengths. Other factors being constant, the frequency of a vibrating string is inversely proportional to its length.* We shorten the strings of a musical instrument to increase the pitch.

PROBLEM. If the D string of a violin is 12 in. long, how much must it be shortened to produce the note E?

*Solution.* D corresponds to 288 vibrations per second and E has a frequency of 320. Then, $288 : 320 = x : 12$. Therefore, $x = 9.6$ in., the length of a string which vibrates 320 times per second. The D string must be shortened 2.4 in. to produce the note E.

2. *Law of diameters. Other factors remaining constant, the frequency of a vibrating string is inversely proportional to its diameter.* On a guitar, for example, the strings that yield the high-pitched notes have smaller diameters. A string 0.1 in. in diameter vibrates twice as fast as a string 0.2 in. in diameter.

3. *Law of tensions. Other factors being constant, the frequency of a vibrating string is directly proportional to the square root of the tension.* When one tunes any stringed instrument, he increases the pitch by tightening the strings.

PROBLEM. A string stretched with a force of 9 lb. gives the note C; with what force would the same string have to be stretched to produce the note C′?

*Solution.* $256 : 512 = \sqrt{9} : \sqrt{x}$. Whence, $x = 36$ lb.

4. *Law of densities. Other factors being constant, the frequency of a vibrating string is inversely proportional to the square root of its density.* The heavier a string, the more slowly it vibrates.

### *B.* MUSICAL INSTRUMENTS

**295. Stringed Instruments.** In a very large number of musical instruments the sound waves come from vibrating strings. The piano, violin, guitar, ukulele, mandolin, and

harp are common examples. In each case some form of sounding board is used. The thin string does not have sufficient area to furnish the required volume of sound, but it forces the sounding board into vibration, even if their natural vibration rates are unequal. Thus the sound is intensified. Pairs of strings are used for certain octaves of the piano to give greater volume; in the treble three strings are used for each note.

**296. Organ Pipes.** In some organ pipes a stream of air is directed against one edge of an opening, as in Fig. 261. A vibrating air-jet is thus produced. The frequency depends upon the length of the pipe, since the vibration rate is influenced by the return of the reflected air pulses. *A closed organ pipe is one fourth as long as the sound wave it produces. An open pipe is one half as long as the sound wave it produces.* To construct a set of organ pipes, their lengths must be made inversely proportional to the vibration ratios given in § 286. The pipes used for one octave, beginning with C, would have lengths of the following ratios: 1, $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, and $\frac{1}{2}$. To summarize, the *pitch of a pipe varies inversely as its length. An open pipe produces a note an octave higher than a closed pipe of the same length.*

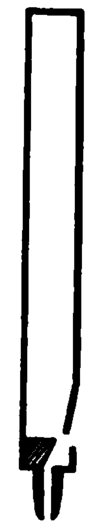


FIG. 261. — Organ pipes.

**297. Overtones in Pipes.** By using greater pressure, it is possible to produce overtones in pipes. In a closed pipe there is always a node at the closed end and a loop or antinode at the open end. For this reason, the only overtones possible in a closed pipe are those whose frequencies are 3, 5, 7, etc., times that of the fundamental. The first overtone of a closed C organ pipe is not C′, but G′, since it has three times the vibration rate of the fundamental.

In open pipes there is a node at the middle and a loop at each end. Consequently the whole series of overtones is possible. When a hole is cut in an open pipe, a loop or anti-

node is produced at this point. This produces the same effect upon the pitch as if the pipe were cut off at that point.

Fig. 262. — Clarinet.

**298. Wind Instruments.** In many wind instruments, a vibrating air-jet is the source of sound. The air-jet may be produced by a vibrating reed as in the organ, French harp, accordion, clarinet, or saxophone. Some organ pipes have a vibrating reed. A bellows is sometimes used to throw the reed into vibration. See Figs. 262 and 263.

In the flute, fife, and piccolo the vibrating air-jet is produced in the same manner as in the organ pipe. A stream of air is directed against the edge of an opening near one end of the instrument. The pitch is regulated by the length.

In the cornet, trombone, and bugle the lips of the player vibrate. The frequency depends upon the length of the tube. In the cornet, openings regulated by valves produce variations in pitch by changing the length of the pipe. See Figs. 264 and 265.

Fig. 263. — Saxophone.

**299. The Player Piano.** In the operation of the player piano large bellows driven by the foot pedals are used to produce a partial vacuum in the wind chest *L*, Fig. 266. A perforated music roll passes over the tracker bar *N*, which has 88 small openings, one for each key of the piano.

From each opening in the tracker bar a tube *M* leads to the wind chest. When the holes in the music roll coincide with the openings in the tracker bar, a pulse of air is sucked into the corresponding tube. This air lifts a leather disc and

FIG. 264. — Cornet.

the valve in one of the pneumatics, thus closing one port and opening the port directly beneath the valve. The air pressure collapses the movable leaf of the pneumatic *H*, which controls the hammers through a set of levers, Fig. 267. The surplus air in the tube is removed through an opening which is called the " bleed."

**300. Vibrations of Bells and Plates.** When bells and plates vibrate, notes are produced which are not *even* mul-

FIG. 265. — Slide trombone.

tiples of the *fundamental*. Although they are not *even* multiples of the fundamental, yet they are called overtones. For this reason chimes are played by striking the bells in succession. Fig. 268 shows some complex figures produced by bowing a metal plate covered with fine sand. Nodes

may be formed at various positions by touching the edge of the plate with the thumb and finger. In each case the plate is touched at *A* and *C* to produce nodes; it is bowed at *B*. The irregularity of the curves shows why it is quite impossible to have such plates produce harmony by simultaneous vibration. The patterns produced in this way are used as designs for wall-paper.

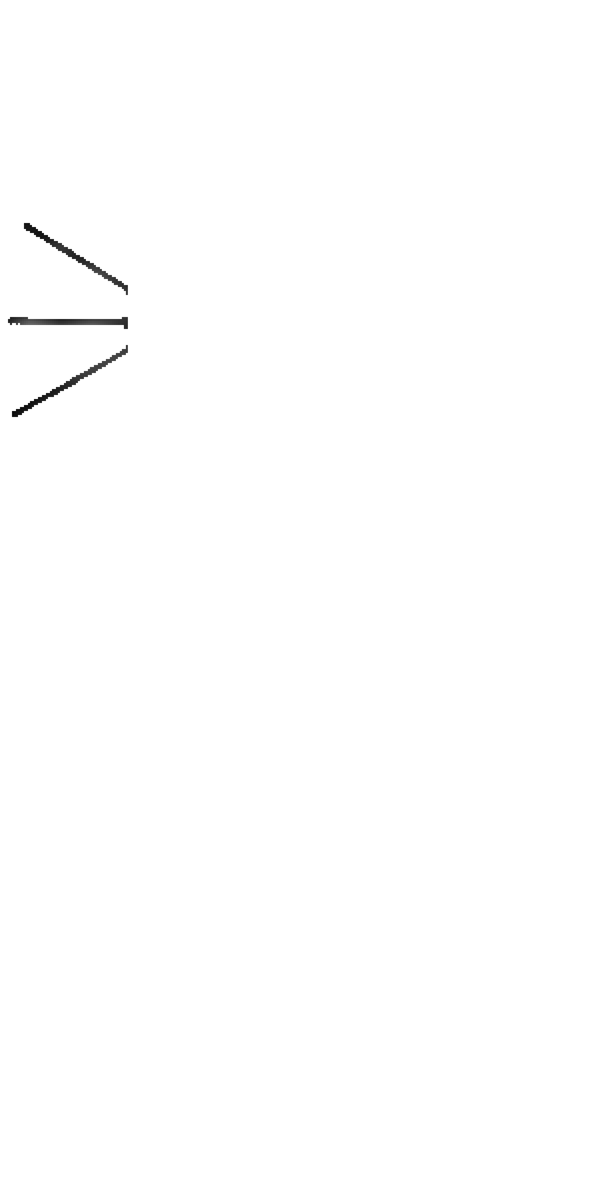


Fig. 266. — Player piano pneumatics.

**301. Vibrating Membranes.** In some musical instruments the vibrating part is a membrane. The tambourine, drum, and kettle drum are examples. The human voice is produced by the vibration of membranes. Two folds of ligamentous membrane which are stretched across the larynx, or Adam's apple, form the vocal cords. By the contraction of certain muscles these cords may be tightened at will. Variations of the tension produce notes of different pitch. In speaking, we learn to modulate the voice by varying the position of the tongue, palate, teeth, and lips. The quality of the voice depends upon the overtones which are made prominent by resonance. By cultivation a person may learn to suppress certain harsh overtones and reinforce others which are more pleasing.

Fig. 267. — Player piano mechanism.

**302. The Phonograph.** This instrument is one of the inventions of Thomas A. Edison. For making the record, a mouthpiece having an elastic disc is used. This disc takes up the vibrations from the voice or some instrument, and, by means of a stylus attached to its center, cuts a groove in a wax cylinder, or traces a zigzag line over a greased metal disc. The metal disc is etched and an electrotype of copper is then made from it. From this electrotype several hundred copies of the original record are made by pressing it into hard rubber, condensite, or some composition material. The sound is reproduced by using a needle which follows the groove that has been made in the record. The needle is carried by a diaphragm, which it throws into vibrations of the same nature as those of the original sound. The diaphragm may be made of mica. In the Edison reproducer it is made of several thicknesses of rice paper shellacked together. Vowel sounds are reproduced with somewhat greater exactness than the consonants, since they are more musical. The quality of the tone produced depends upon the needle used and upon the resonance of the framework of the instrument. Irregularities in the record itself may produce surface noises or scratching. With some records the groove is a lateral cut, and the reproducer is held in a vertical position, as shown in Fig. 269. In other cases,

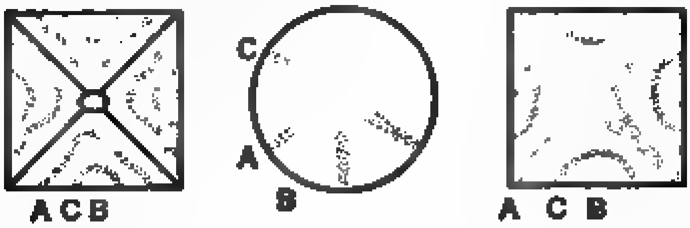


Fig. 268. — Vibrating plates.

Fig. 269. — Phonograph reproducer (lateral).

the cut is "hill and dale," so the diaphragm must vibrate up and down. The reproducer is held in the horizontal position shown in Fig. 270.

**303. Sound Waves Shown Graphically.** A number of different methods of recording sound waves are now in use.

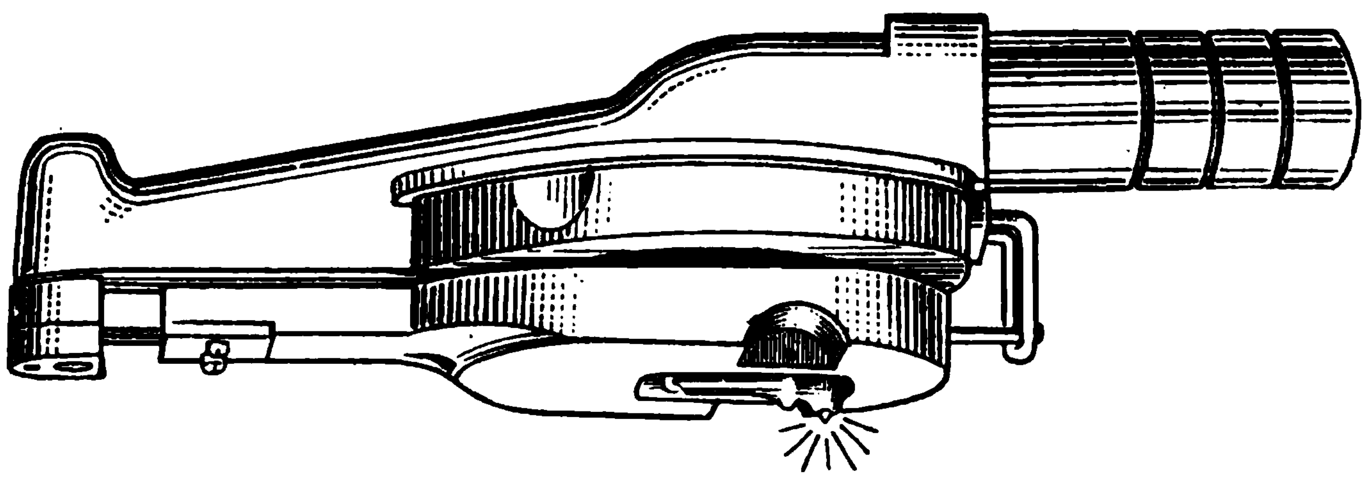


FIG. 270. — Phonograph reproducer (hill and dale).

In one of the simplest methods a stylus is fastened to a tuning fork, the stem of which is held firmly. A piece of smoked glass is then drawn beneath the fork so the point of the stylus traces its vibrations on the smoked glass. A smoked cylinder may be used in a similar manner.

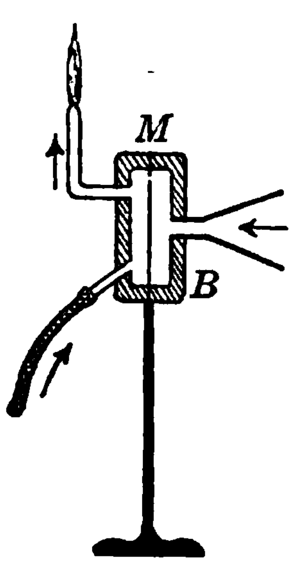



FIG. 271. — Manometric flame apparatus.

One early method used to picture sound waves was devised by Koenig. In the *manometric flame* apparatus, Fig. 271, *M* is an elastic membrane separating the two compartments of block *B*. There are two openings to the left-hand compartment, one fitted with a jet tube; the other is fitted with a tube connected to a gas-cock. The right-hand compartment has a single opening fitted with a funnel tube. The sound waves that enter this tube cause a corresponding vibration of the elastic membrane. As the condensations and rarefactions alternately compress the gas and then permit it to expand, the flame vibrates simultaneously. The vibrations of the flame are too rapid to be

seen without the aid of a revolving mirror. When the membrane is not vibrating, a continuous band appears on the revolving mirror. An object sounding its fundamental produces a series of zigzag lines all of the same length. When overtones are produced with the fundamental, the lines are of varying length.

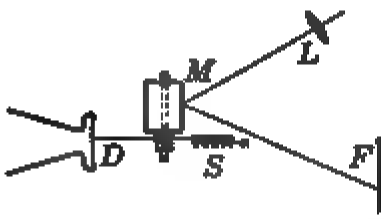


FIG. 272. — Phonodeik.

The *phonodeik* was invented by Dr. Dayton C. Miller of the Case School of Applied Science. By its use it is possible to photograph the wave forms of various instruments, or of the human voice. In Fig. 272, *M* is a tiny mirror which is free to oscillate on a small steel shaft mounted in jeweled bearings. A thin glass diaphragm *D* is set in the horn of a resonator. One end of a fine thread is attached to this diaphragm. The thread is then wrapped around a small pulley mounted on the mirror shaft, and the other end is fastened to a tension spring *S*. A narrow pencil of light from the lens *L* is focused on the mirror, from which it is reflected to a sensitized film *F*, which moves at right angles to the mirror. As the sound waves enter the horn of the resonator the diaphragm is thrown into vibration. These vibrations are transmitted through the thread to the mirror, causing it to oscillate on its axis. The pencil of light reflected from the mirror traces

FIG. 273. — Vowel sound *oo* as in mood.

FIG. 274. — Vowel sound *ee* as in feed (note overtones).

FIG. 275. — Sound vibrations photographed by Dr. Dayton C. Miller of the Case School of Applied Science. Music, sextette from Lucia. Top line, as sung by Caruso. Second line, as sung by Tetrazzini. Third line, as sung by Amati and Tetrazzini. Bottom line, as sung by the sextette. The numbers show the time of exposure of film in tenths of seconds Time for top score, one second. The modern phonograph makes it possible to engrave the vibrations of the human voice on permanent records made of wax, gutta-percha, or some other plastic, and then reproduce them at pleasure. Dr. Miller's phonodeik photographs the sound vibrations and enables us to study the fundamentals and overtones produced by the voices of renowned artists.

on the film the sound waves that act upon the diaphragm. Figs. 273 and 274 show the fundamentals and overtones produced by vowel sounds. Some of the effects produced by singing voices are represented in Fig. 275.

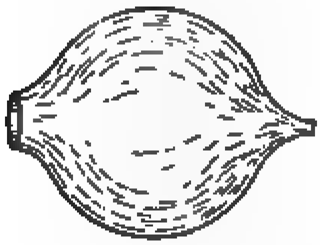


FIG. 276. — Helmholtz resonator.

**304. Helmholtz Resonators.** Complex sounds may be analyzed and studied by means of a set of resonators of the type devised by Helmholtz. See Fig. 276. The series of resonators consists of a set of hollow spheres, of such size that each one produces resonance with a note of a certain pitch. By placing the large opening near a body producing complex sounds and holding the small opening to the ear, it is possible to pick out all the overtones that are present if a series of resonators is used one after another.

Complex sounds have been analyzed by this method and then reproduced by using electrically driven tuning forks to represent each of the various frequencies that were identified by the resonators. See Fig. 277.

FIG. 277. — Electrically driven tuning fork.

## SUMMARY

The major chord is built up of notes whose frequencies have the ratios 4, 5, 6, and 8. The major diatonic scale consists of eight notes in each octave for any given key. The chromatic scale adds five notes per octave. In the equally tempered scale, the interval is uniform; the twelfth root of two is used.

Discord is a phenomenon of beats. About 30 beats per second produce the worst possible discord. If fewer than 5, or more than 60 beats reach the ear per second, the notes are not discordant.

A string vibrating as a whole produces its fundamental, or the note of lowest pitch it can give. A frequency which is a multiple of the fundamental is called an overtone.

The frequency of a vibrating string is inversely proportional to its length, diameter, and the square root of its density; it is directly proportional to the square root of the tension.

In musical instruments the sound waves are generally caused by vibrating strings, or air-jets. Air-jets may be set up by reeds, by the vibrations of the lips of the player, or by striking the edge of an opening.

A closed organ pipe is one fourth as long as the sound wave it produces; an open pipe is one half as long as the sound wave it produces.

In an open pipe the whole series of overtones is possible; in a closed pipe only those overtones whose frequencies are *odd* multiples of the fundamental are possible.

The overtones of bells and plates are not multiples of the fundamental. They do not produce harmony when struck simultaneously.

Complex sounds may be analyzed graphically by the manometric flame; the Helmholtz resonators are also used to pick out the overtones in complex sounds.

## QUESTIONS AND PROBLEMS

1. What is the first overtone of C? of G? of E′?

2. Why is there a discord when C and B are struck at the same time?

3. What is the vibration rate of the sixth overtone of C? To what letter on the scale does it correspond? Why is it desirable to suppress the sixth overtone?

4. Why is a violin string bowed near one end instead of in the middle?

5. How is the pitch varied in ordinary whistling?

6. Do sound waves ever cast shadows?

**7.** Why does pressing the soft pedal of a piano decrease the loudness? Is the mechanism for softening the same with upright and grand pianos? Explain.

**8.** Why does the pitch rise as water is poured into a tall cylinder?

**9.** Does pressing either the loud or soft pedal of a piano affect the pitch of the notes? Explain.

**10.** Compare the frequencies of two strings. *A* is one meter long and 0.5 mm. in diameter. *B* is 50 cm. long and 1 mm. in diameter.

**11.** A string stretched by a force of 25 Kgm. gives the note E. What stretching force is required to produce the note G?

**12.** How long must a closed pipe be to give the note G? the note E′?

**13.** What is the first overtone of an open pipe that gives the note C′? What is the first overtone of a closed pipe that gives the note C′? The second overtone?

**14.** Several notes may be blown on a bugle of unvarying length. Explain.

**15.** How does opening the holes of a saxophone or clarinet affect the pitch?

**16.** A piano is properly tuned when the temperature is 70° F. Is it in tune when the temperature is 80° F.?

**17.** Why does increasing the speed of a phonograph raise the pitch? Why does a short needle make the sound louder?

**18.** What is the frequency of the lowest note on the piano, $A_4$, a little more than three octaves below middle C? What is the vibration rate of C′′′′?

**19.** How is the quality of the human voice modified? Where is the resonance produced?

**20.** What laws of strings are illustrated in the construction, tuning, and playing of the violin?

# CHAPTER 16

# LIGHT

## A. NATURE AND VELOCITY

**305. Nature of Light.** Although Huygens proposed the wave theory of light as early as 1678, it was not generally accepted before the beginning of the nineteenth century. Prior to that time the corpuscular theory met with greater favor. It was believed that small particles or corpuscles are projected from a luminous body, producing the sensation known as *light*.

It is a fact capable of demonstration that sound is transmitted to the ear by means of waves traversing some medium. In the study of heat we learned that heat energy may be transmitted by waves in the ether, and it is now generally believed that ether waves may produce various effects. They may affect the receiver of a wireless outfit, change the chemical nature of a photographic plate, increase the temperature of a body, or produce the sensation of light. The effect they produce seems to depend upon their length. Ether waves that affect the optic nerve are called light waves. The optic nerve is sensitive only to those ether waves which have certain lengths. Heat waves and wireless waves are longer than light waves; some waves that affect the photographic plate and do chemical work are much shorter.

**306. Light Waves Differ from Sound Waves.** There are several ways in which light waves differ from sound waves: (1) Light waves travel through a vacuum, while sound waves do not; (2) light waves are ether waves,

**7.** Why does pressing the soft pedal of a piano decrease the loudness? Is the mechanism for softening the same with upright and grand pianos? Explain.

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**306. Light Waves Differ from Sound Waves.** There are several ways in which light waves differ from sound waves: (1) Light waves travel through a vacuum, while sound waves do not; (2) light waves are ether waves,

while sound waves travel through matter; (3) light waves are transverse, while sound waves are longitudinal; (4) sound waves bend around corners readily, but light waves travel in straight lines; (5) sound waves vary in length from one cm. to about 21 m., while light waves vary in length from 0.000039 cm. to 0.000081 cm.; (6) the speed of sound is very slow compared to that of light.

**307. Sources of Light.** Nearly all the *natural* light we receive comes from the sun. Some of the stars are much larger than our sun and give off more light, but they are so far away that we receive only a very small portion of the light they give off. Dr. Michelson of the University of Chicago recently found a method of measuring the diameter of one of the stars. He learned that Betelgeuze, a star in the constellation Orion, has a diameter much greater than that of our sun. If this star were placed in the center of our solar system, its edge would extend beyond the position of the planet Mars, about 150,000,000 miles from the center of the sun. This star has a diameter of about 300,000,000 miles. *Artificial* light is produced by the combustion of oil or gas. Light is also produced artificially when an object is heated until it glows. The incandescent electric light and the Welsbach gas light are examples.

Any object that gives off light on account of the energy of its own oscillatory particles is said to be *luminous*. When a platinum wire is heated the ether waves which are set up gradually grow shorter as the temperature rises. The wire soon begins to glow, or we say it is *incandescent*. It is now a luminous body, visible on account of its own light. *Illuminated bodies* merely reflect light which they have received from other sources. The moon is an illuminated body, giving off only the light it has received from other sources.

**308. Reflection, Absorption, and Transmission of Light.**

When light waves are incident upon a body, they may be affected in different ways:

(1) Some rays are *reflected*, or turned back. Polished metals reflect a large part of the light waves they receive. Glass and water are also good reflectors.

(2) Part of the rays are *absorbed*. When the *vertical* rays of the sun fall upon a body of water, they are largely absorbed or transmitted; when the sun's rays strike the water at a very *oblique* angle, as when the sun is setting, more of the rays are reflected. Dark-colored objects are good absorbers.

(3) Part of the rays are *transmitted*. Any substance that transmits light so readily that objects are easily distinguished through it is said to be *transparent*. *Translucent* substances transmit considerable light, but they diffuse the light so much that objects cannot be clearly distinguished through them. *Opaque* objects do not transmit light. No substance is perfectly transparent, since the clearest water, or air itself, absorbs some light. On the other hand, no object is perfectly opaque. Very often all three of these effects are produced at the same time, a part of the light being reflected, a part absorbed, and the rest transmitted.

**309. Rays, Beams, and Pencils of Light.** Light is emitted in all directions from a luminous point. If the medium is of the same nature throughout, light travels in straight lines. The sighting of a rifle depends upon this fact. A single line of light coming from a luminous point is called a *ray*. Several rays proceeding toward a point form a *converging pencil*. Several rays of light proceeding from a point produce a *diverging pencil*. Several parallel rays form a *beam* of light. The rays of light coming from the sun are so nearly parallel that we may consider them beams of light.

**310. Shadows.** Since an opaque body absorbs light, the space behind it is in darkness. Any space from which the rays of light are excluded by an opaque object is called

a *shadow*. When the source of light is a point, as in Fig. 278, all the rays will be cut off from the dark part of the screen $S$ by an opaque ball $B$. If the light comes from a spherical object, the shadow will vary in intensity. See Fig. 279. The part from which all the rays of light are excluded, included in the cone $DCF$, is called the *umbra*. The length of the umbra depends upon the relative sizes of the luminous and opaque objects and upon the distance between them. The lighter parts of the shadow, $CFy$ and $CDx$, are called the *penumbra*. Suppose we let $S$ represent the sun in Fig. 279, $E$ the earth, and $M$ the moon. It is easy to see that an eclipse of the moon is caused by the earth intercepting the sun's rays; the moon is just entering the umbra of the earth's shadow. During an eclipse of the sun, the sun's rays are cut off by the moon so that they do not reach the earth's surface. When the moon is in the position shown at $M'$, the sun will be totally eclipsed for an observer any place on the earth between $R$ and $T$.

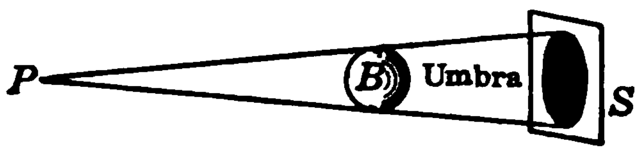


FIG. 278. — Umbra, or dark shadow.

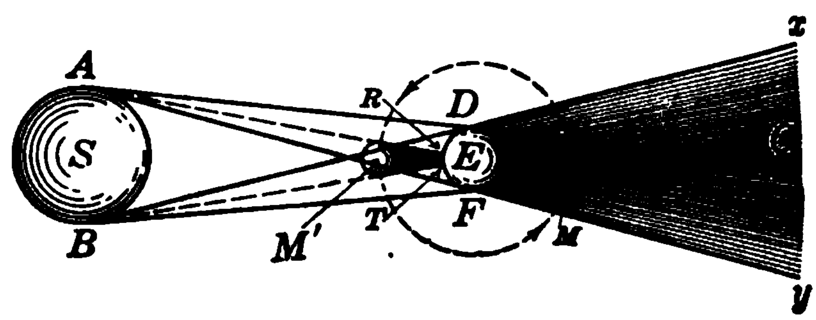


FIG. 279. — Penumbra and eclipses.

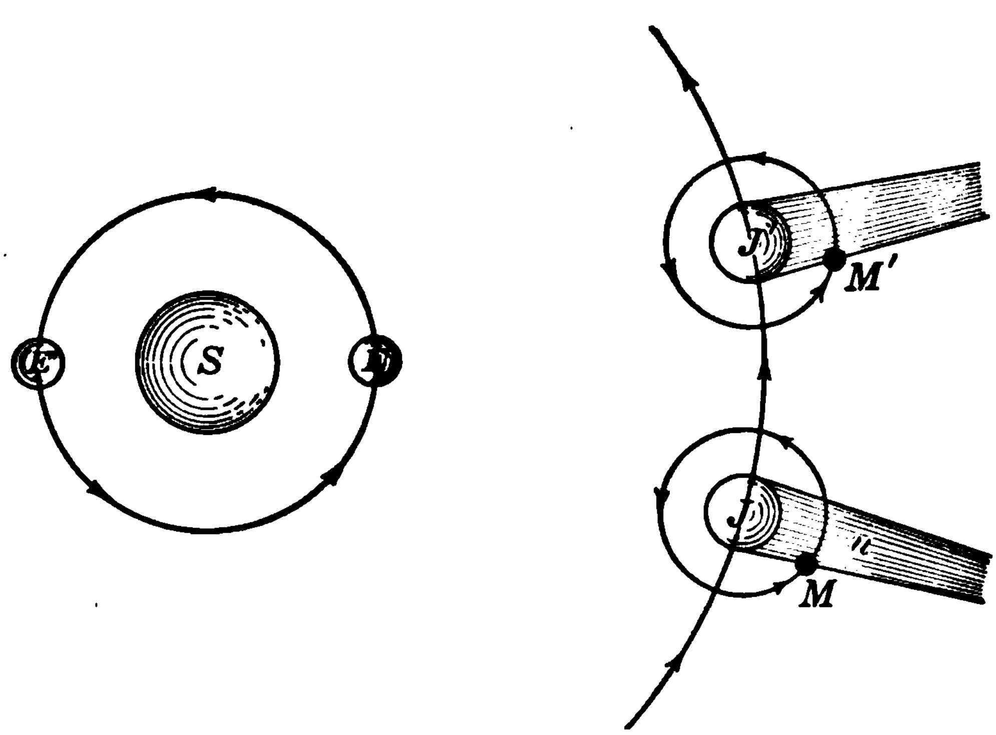


FIG. 280. — To show how velocity of light was determined.

**311. Velocity of Light.** Prior to 1675, Galileo's conclusion that light is instantaneous was generally accepted. In that year Roemer, a Danish astronomer, found a method for determining the velocity of light. In Fig. 280, $M$ is one of Jupiter's moons, which is eclipsed as it enters the umbra at $U$. Roemer determined the time required for a revolution of this satellite of Jupiter. After observing the time of the eclipse when the earth was at position $E$ in its orbit and Jupiter at position $J$, Roemer calculated the time that the eclipse should occur six months later when the earth would be at position $E'$ and Jupiter at $J'$. The eclipse occurred 16 min. and 36 sec. later than the time calculated. Since the earth at the later date was about 186,000,000 miles farther away, from $E$ to $E'$, Roemer reasoned that the 996 sec. difference was the time required for the light to cross the earth's orbit. He concluded that the velocity of light was a little more than 186,000 miles per second.

Other methods for finding the velocity of light were used by Foucault in France, and Michelson of the University of Chicago. These observers found that light has a velocity of a little more than 186,000 miles per second. They also determined the velocity of light in some solids and liquids. The velocity in water is about three fourths as great as in air; in ordinary glass it is about two thirds the speed in air. Light travels slightly faster in a vacuum than it does in air.

## *B.* PHOTOMETRY

**312. Illumination.** The amount of light we receive depends upon two factors: the *intensity* of the light, and the *distance* we are from it. We know that the light grows dimmer as we move farther away. Fig. 281 helps us to understand why this is true. The screen $A$, which has an

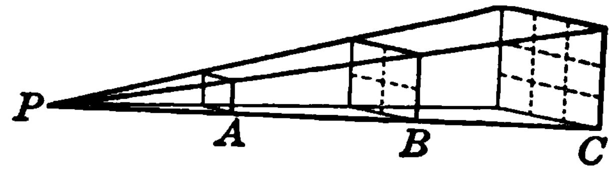


FIG. 281. — Effect of distance on amount of illumination.

area of 1 sq. ft., is 1 ft. from a light; *B*, which is four times as large, is 2 ft. distant; and *C*, which has nine times the area of *A*, is 3 ft. away. If we remove screen *A*, then *B* will be illuminated by the same rays from the light *P* that *A* had received. But since *B* has an area of four sq. ft., 1 sq. ft. of its surface will receive only one fourth as much light as the same area did at position *A*. Likewise, *C* is three times as far away as *A*, and the light will be spread over nine times the area. Thus 1 sq. ft. of surface receives only one ninth as much light at *C* as at *A*. Therefore we conclude *that the amount of light a body receives is inversely proportional to the square of its distance from the source of light.* This statement is known as the *law of illumination.*

Conversely, if we wish to illuminate unit area of screen *C* as strongly as screen *A*, it will be necessary to use a light whose intensity is nine times as great as that at *P*. To secure equal illumination, the *candle powers must be directly proportional to the squares of the distances from the screen.* This is the *law of intensity.*

**313. The Standard Candle.** The intensity of a light is expressed in candle power. The standard formerly used was a sperm candle burning 120 gr. of wax per hour. At present incandescent electric lights are nearly always used instead of the standard candle. The ordinary arc light gives about 500 candle power; the flaming arc gives 800 or more. Incandescent lamps used for interior lighting generally range from 8 candle power to 100, although high candle power, argon-filled lamps are sometimes used.

If we observe closely the ordinary tungsten lamp suspended vertically with the shade removed, we notice that the light emitted horizontally is much more intense than that given off vertically. Candle power may refer to horizontal illumination, or to illumination in any direction. The candle power of the arc light as already given is the

average of the candle powers in all directions, or its *mean spherical* candle power. The maximum candle power of the arc light is much more than 500.

**314. Amount of Light Needed.** When we read it is not so important to consider the candle power of the light we are using, as it is to determine how much the page is illuminated by that light. The standard of illumination is the *foot-candle;* it is the amount of light one would receive from a standard candle at the distance of one foot. Candle power is based upon intensity only. The foot-candle depends upon intensity and distance. A person seated 1 ft. from a 16 C.P. lamp receives 16 foot-candles; if he is 2 ft. from the same lamp, he receives only 4 foot-candles. ($16 \div (2)^2$.) The number of foot-candles needed varies with the kind of work. For reading ordinary print, or for writing, or for work on light-colored material, from 2 to 4 foot-candles are usually sufficient. Reading from finer type may require 6 foot-candles, while from 8 to 10 foot-candles may be needed for such work as sewing on black goods. In houses lighted by electricity many persons use more foot-candles than are necessary. Eye-strain may result from too much light as readily as from too little.

**315. Photometry.** Photometry is that branch of science which deals with the measurement of the intensity of light. Several types of photometers have been devised In the Bunsen photometer, Fig. 282, a piece of paper, in the center of which there is a grease spot, is moved along a meter stick between a standard candle and the lamp of unknown candle power. If we hold such a sheet of paper toward the light, the grease spot appears lighter than the surrounding paper, since it transmits light better. If, however, we turn the paper from the window, it appears darker, since the grease

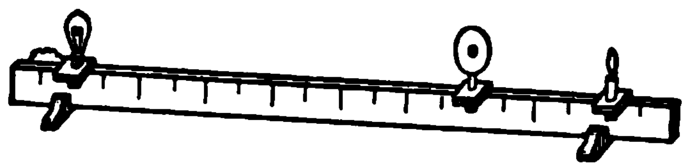


FIG. 282. — Bunsen photometer.

## QUESTIONS AND PROBLEMS

**1.** Could there be an eclipse of the moon at new moon? Give a reason for your answer.

**2.** The North Star is so far away that it takes about 55 years for its light to reach the earth. How far away is it in miles? Give a probable reason why astronomers express the distance of stars in light-years.

**3.** *A* is seated 2 ft. from a lamp; *B* is 3 ft. from the same lamp. Compare the amount of light each receives.

**4.** In using a photometer the screen is found to be equally illuminated when a 16 C.P. lamp is 10 cm. away and an arc lamp of unknown C.P. is 65 cm. distant. What is the candle power of the arc lamp?

**5.** At one end of a meter stick is a 32 C.P. lamp; at the other end there is a 9 C.P. lamp. Where must a screen be placed between them to be equally illuminated? (*Hint.* Let $x$ equal one distance, and $100-x$ the other.)

**6.** A stick 4 ft. long casts a shadow 5 ft. long; how high is a flag-staff which casts a shadow 100 ft. long?

**7.** The planet Mars is about 140,000,000 miles from the sun. The earth is about 92,000,000 miles. Compare the relative amount of heat and light received from the sun by these two planets.

**8.** In Fig. 279, the radius *AS* of the sun is 433,000 miles; the radius *ED* of the earth is 4000 miles; the distance *SE* between the sun and the earth is 92,500,000 miles. Find *EC*, the length of the earth's shadow. (*Hint.* Note that *ASC* and *DEC* are similar triangles. *SC* equals 92,500,000 miles plus $x$ miles.)

**9.** A is reading by the light of a 16 C.P. lamp 2 ft. away; B reads by the light of a 40 C.P. lamp 4 ft. away. How many foot-candles of light does each receive?

**10.** A pin-hole camera has a sensitive plate $4 \times 4$ in. The box is 6 in. long. How far away must a man 6 ft. tall stand for a full-length image to be formed?

**11.** A tree 60 ft. high is 180 ft. distant. How far from the eye must a pencil 6 in. long be held to appear the same height as the tree?

**12.** The moon is about 240,000 miles from the earth. Draw

a diagram to show that the sun can never be in total eclipse except for a very small portion of the earth at any given time.

**13**. A public reading room has 12-foot ceilings. Which is better, to light the room with 4 arc lights of 500 C.P. each, suspended 2 ft. from the ceiling, or to use 16 incandescent lamps of 100 C.P. each, suspended 5.5 ft. from the ceiling? (Assume that the reading tables are 30 in. high.) Figure the maximum number of foot-candles a reader would receive per lamp in each case.

*Suggested Topic.* Proper Arrangement and Use of Lights.

# CHAPTER 17

## LIGHT — REFLECTION

**317. Reflection of Light.** The amount of light an object reflects depends upon the *nature of the material,* the *polish of the surface,* and the *angle at which the light strikes the surface.* Polished metals are generally excellent reflectors. The glare of the rising or setting sun upon the water teaches us that more light is reflected when the rays are incident upon the surface at an oblique angle. At noonday it is not difficult to look at the image of the sun in the water, because perpendicular rays are more readily absorbed.

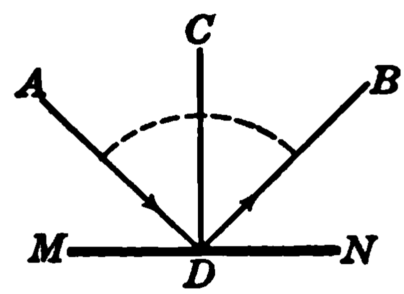



FIG. 285. — Law of reflection.

**318. Law of Reflection.** In Fig. 285 let $MN$ represent a reflecting surface. $CD$ is perpendicular to the reflecting surface; in physics it is generally called the *normal.* $AD$ is a ray of light incident upon the mirror at $D$; and $DB$ is the path of the reflected ray. The angle $ADC$ is the *angle of incidence;* the angle $BDC$ is the *angle of reflection. In all cases the angle of incidence is equal to the angle of reflection;* the incident ray, the reflected ray, and the normal all lie in the same plane.

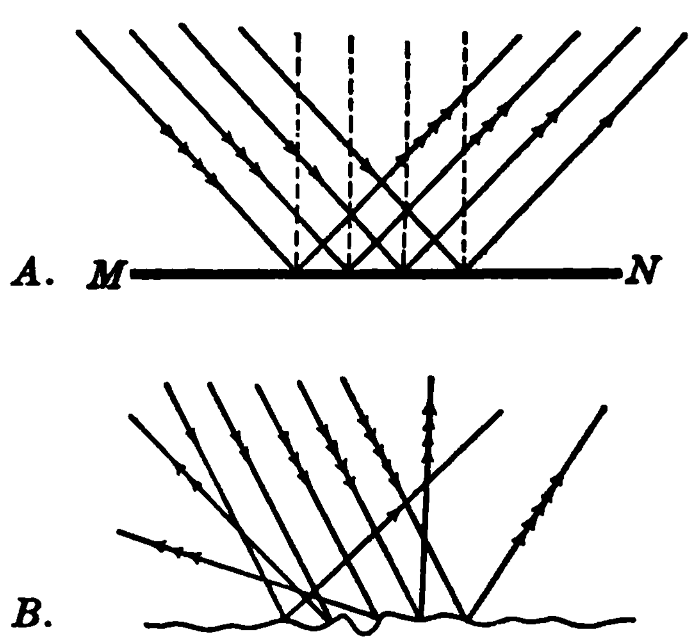



FIG. 286. — *A.* Regular reflection. *B.* Irregular or diffused reflection.

**319. Diffused Reflection.** If we examine Fig. 286 *A,* we see how a beam of light

is reflected from a polished surface. The incident rays are parallel, and the reflected rays that leave the mirror are also parallel. Suppose a beam of light falls upon an irregular surface as in Fig. 286 *B*. The law of reflection holds true, but the normals to the surface are not parallel, hence the light is scattered in all directions. The importance of such scattering or *diffusing* of light can hardly be over-estimated. It renders non-luminous objects visible. The fact that one may walk into large mirrors or plate glass is evidence that neither perfect reflectors nor transparent objects are easily visible. Every one is familiar with the dazzling rays of the sun when reflected from a mirror as a single beam. For this reason it is difficult to read from highly glazed paper in a strong light. Furthermore, if the sun's rays were not diffused, the corners of a room and the space under shade trees would be in almost total darkness. The dust particles in the air are very important factors in the diffusion of light. The frosted light bulb, unglazed print paper, and rough wall-paper are all examples of efforts made to promote the diffusion of light.

**320. Mirrors.** A mirror is a highly polished surface that is used to form images by the regular reflection of light. Mirrors are of two kinds: *plane* and *spherical*. Spherical mirrors may be either *concave* or *convex*. When the outside surface of a sphere is used as the reflecting surface, the mirror is convex; the inside surface of a hollow sphere forms a concave mirror. Sometimes curved mirrors are made by using the surfaces of a cylinder as the reflecting surfaces.

**321. Kinds of Images.** When rays of light are so reflected that they meet in front of the mirror, they form a *real* image. Since the image is produced by the actual rays of light themselves, such an image can be thrown upon a screen. A real image is always inverted. An image that is formed behind the mirror is *virtual*. The rays of light *appear* to meet back of the mirror to form such an image. *A virtual*

or *apparent* image is always erect; it cannot be thrown upon a screen.

**322. Images Formed by Plane Mirrors.** It is very easy to construct the image formed by plane mirrors. In Fig. 287, let $MN$ represent the mirror, and $ABC$ the object whose image we wish to construct. Let us arrange two pins, $E$ and $D$, in line with the image of point $A$ as seen in the mirror; this image will fall some place on the line $ED$ produced. In the same way we may set two pins, $x$ and $y$, in line with the image of $A$. Now the image of $A$ will also be at some point on this line produced. Since $A'$ is the only point common to both lines, we locate the image of $A$ at the point $A'$. By using the same method we can locate the image of $B$ at $B'$, and the image of $C$ at $C'$. This method of constructing the image of an object also verifies the law of the reflection of light. The ray of light $AO$ coming from point $A$ is reflected at $O$ along the line $DE$. If we bisect the angle $AOE$, the bisector $OR$ is normal to the mirror.

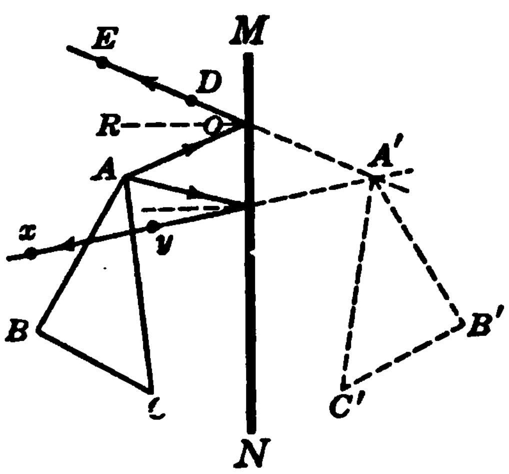


Fig. 287. — Images in plane mirrors.

The *images formed by plane mirrors are always virtual, erect, the same size as the object, and as far behind the mirror as the object is in front.* It will also be observed that the image of each point is on the normal produced behind the mirror. The image is reversed, so that the left side becomes the right and vice versa.

**323. Uses of Plane Mirrors.** From the very earliest times mirrors have been used as looking glasses. They are frequently used by the army signal corps for flashing signals. Since the image is virtual, it is possible to use plane mirrors for producing optical illusions on the stage. In the production of the stage ghost the audience looks through a large piece of plate glass and

sees upon the stage the virtual image of an actor who is behind the scenes.

**324. Multiple Reflection.** Just as sound waves bound and rebound between parallel cliffs or walls to produce echoes and reëchoes, so light waves are reflected back and forth between parallel mirrors or mirrors set at an acute angle, forming multiple images. The image formed in one mirror acts as the object which forms an image in the second mirror. Another image of this image may then be formed. Since some light is absorbed each time, each succeeding image is fainter than the one just preceding. The kaleidoscope is an example of multiple reflection. Three mirrors set at angles of 60° form multiple images of vari-colored pieces of glass.

A thick plate-glass mirror also shows multiple reflection because both surfaces are reflectors. Fig. 288 shows how the ray of light $AB$ is partially reflected to $C$; a part passes through the glass to $D$, the back of the mirror, whence it is again reflected. The path the ray may take is shown by the arrowheads. When it reaches the front surface it is divided; a part enters the air, and a part is reflected to the back surface again. A gas-jet or electric light as viewed in a plate-glass mirror shows such a series of images.

Fig. 288. — Multiple images.

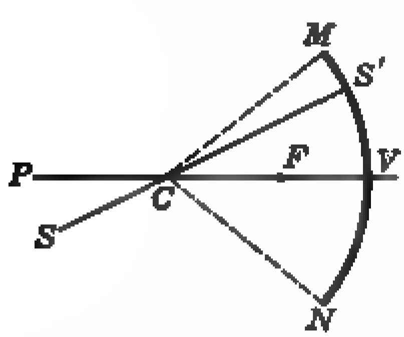



Fig. 289. — Definitions pertaining to curved mirrors.

**325. Definition of Terms.** Before the student can understand how images are formed by curved mirrors, several terms must be defined. Assuming that the mirror is part of the surface of a sphere, let us use Fig. 289 to help make these definitions clear. (1) The *center of curvature* $C$ is the center of the sphere

of which the mirror is a part. (2) The *aperture* is the angular portion *MCN* of the sphere included by the mirror. (3) The *vertex* *V* is the center of the mirror itself. (4) The *principal axis* is the line *PV* drawn through the center of curvature and the vertex. (5) Any other line drawn through the center of curvature, *SS'* for example, is called a *secondary axis*. (6) A *focus* is a point where the rays of light meet, or appear to meet. Rays of light parallel to the principal axis are reflected and meet at the *principal focus*, *F*. The principal focus is on the principal axis, *midway between the center of curvature and the vertex*. (7) The distance from the principal focus to the vertex is the *focal length*, *FV*. It is one half the radius of the sphere of which the mirror is a part. (8) The *normal* to the surface of a concave mirror is the radius drawn from the point of incidence. In the case of the convex mirror, it is the radius produced.

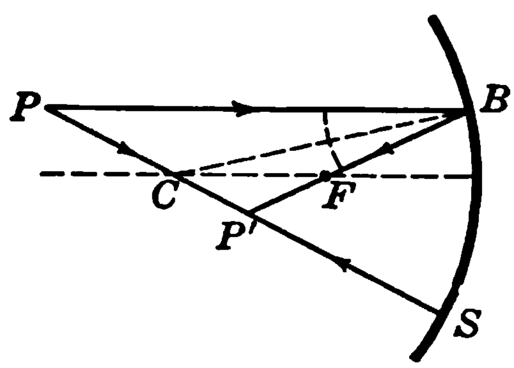


FIG. 290. — Image of point formed by curved mirror.

**326. Construction of the Image of a Point in a Spherical Mirror.** To construct the image of point *P* formed by a concave mirror Draw the principal axis. See Fig. 290. Since light is given off in all directions from the point *P*, we may draw *any two* lines incident upon the mirror and find where they intersect after reflection. In all construction work care must be taken to make the angles of incidence and reflection equal. It is easier to use for one line the secondary axis, since it is incident upon the mirror at an angle of 90° and it is reflected directly back upon itself. *The image of a point is always some place on its secondary axis.* Let us draw the secondary axis *PS* from *P* to the mir-

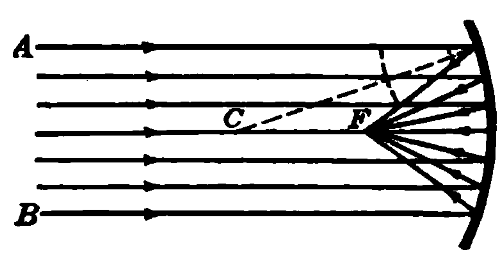


FIG. 291. — Object at infinite distance. Case 1.

ror. The image of $P$ will lie at some point on $PS$. Since all rays *parallel* to the principal axis are reflected back through the principal focus, the next easiest line to trace is one parallel to the principal axis. Draw $PB$ parallel to the principal axis, and then the reflected ray $BF$ through the principal focus. The image of $P$ is some place on $BF$. But $P'$ is the only point common to $PS$ and $BF$; therefore the image of $P$ is formed at $P'$. To prove that $PB$ passes through $F$ by reflection, draw the normal $BC$. If the work has been accurately done, the angles $PBC$ and $CBF$ will be equal.

FIG. 292. — Optical disc. Reflection from concave mirror.

**327. Images Formed by Concave Mirrors.** It is possible to distinguish six quite distinct cases for the formation of images by concave mirrors, depending upon the distance of the object from the mirror.

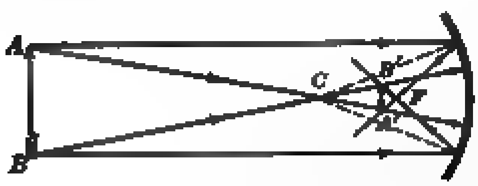


FIG. 293. — Object at finite distance. Case 2.

CASE 1. *When the object is at an infinite distance, the image is a point at the principal focus.* From Fig. 291 we see that all the rays incident upon the mirror are parallel. They will all be reflected back to the principal focus. The image formed is a point. See Fig. 292.

CASE 2. *When the object is at a finite distance beyond the center of curvature, the image is real, inverted, smaller than the object, and located between the center of curvature and the principal focus.* See Fig. 293. The image increases in size as the object is brought nearer the center of curvature.

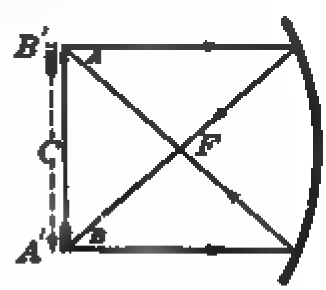


FIG. 294. — Object at center of curvature. Case 3.

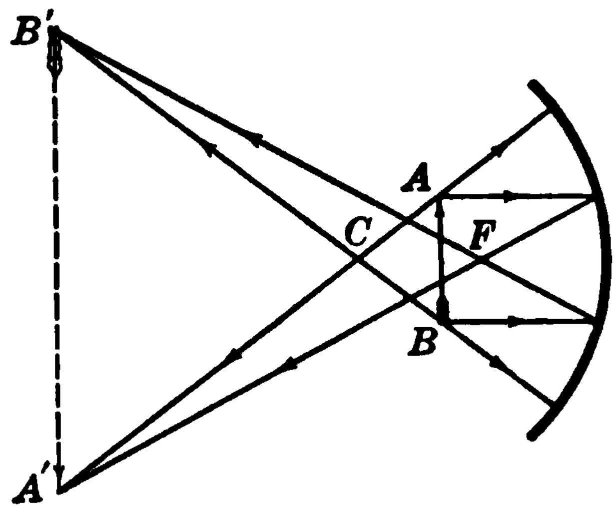



FIG. 295. — Object between $C$ and $F$. Case 4.

CASE 3. *When the object is at the center of curvature, the image is real, inverted, the same size as the object; it is formed at the center of curvature.* In constructing the image, the secondary axes are not shown, since the aperture of the mirror is not large enough to include them. See Fig. 294.

CASE 4. *When the object is between the center of curvature and the principal focus, the image is real, inverted, larger than the object, and beyond the center of curvature.* This case is the converse of Case 2. Fig. 295.

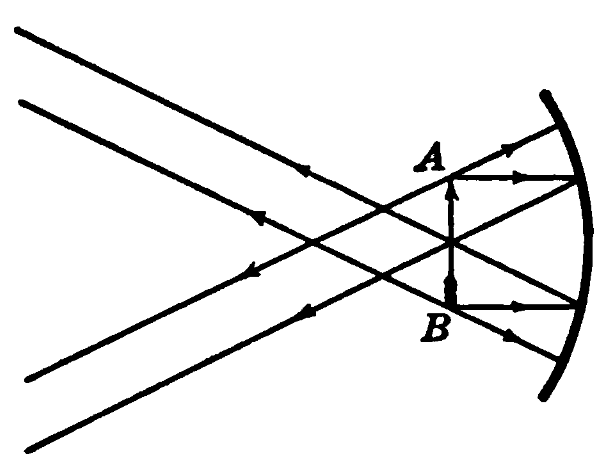



FIG. 296. — Object at principal focus. Case 5.

CASE 5. *When the object is at the principal focus, the rays of light are parallel as they leave the mirror and no image is formed.* This case is the converse of Case 1. See Fig. 296.

CASE 6. *When the object is between the principal focus and the vertex, the image is erect, enlarged, virtual, and behind the mirror.* See Fig. 297.

**328. Images Formed by Convex Mirrors.** In *convex mirrors the image formed is always virtual, erect, smaller than the object, and between the mirror and the principal focus.* As the object is brought nearer the mirror, the image gradually increases in size, becoming nearly as large as the object when it is very near the mirror. Fig.

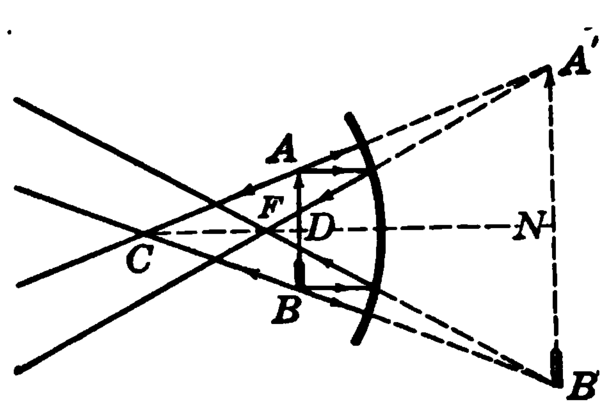



FIG. 297. — Object between $F$ and mirror. Case 6.

298 shows the formation of images by convex mirrors. The optical disc of Fig. 299 shows how parallel rays of light are scattered by a convex mirror.

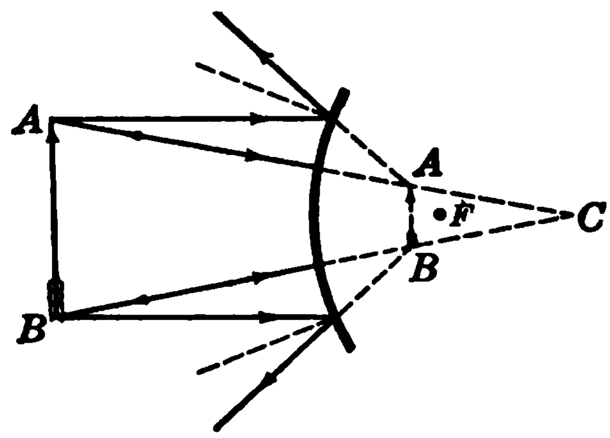



FIG. 298. — Images by convex mirror.

**329. Applications.** Case 1 may be used to find the focal length of a mirror. The sun is so far away that its rays are practically parallel; they are therefore so reflected that they meet at the principal focus. The distance from the principal focus to the mirror is the focal length. Case 3 may also be used for this purpose, since the focal length is just one half the radius. Either Case 2 or Case 4 may be used to throw an inverted image on a screen. In Case 4 the image is enlarged, while in Case 2 it is reduced. The so-called shaving mirror is an application of Case 6. A modification of this case is used in lamp reflectors, and in the headlights for automobiles, street-cars, and locomotives. The light is put a little nearer the mirror than the principal focus so the rays will be slightly divergent, as shown in Fig. 300. When a concave mirror is used in searchlights, the lamp is so near the focus that the rays are nearly parallel. The *ophthalmoscope* is a concave mirror with a small hole in its center. By using this instrument, a physician can reflect light into a patient's eye, and at the same time look into the eye through the hole in the mirror.

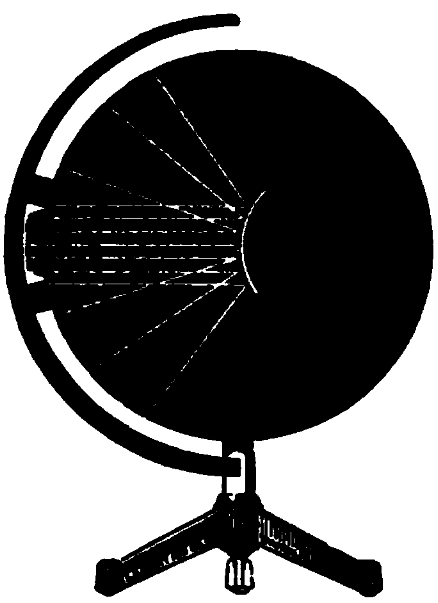


FIG. 299. — Reflection from convex mirror.

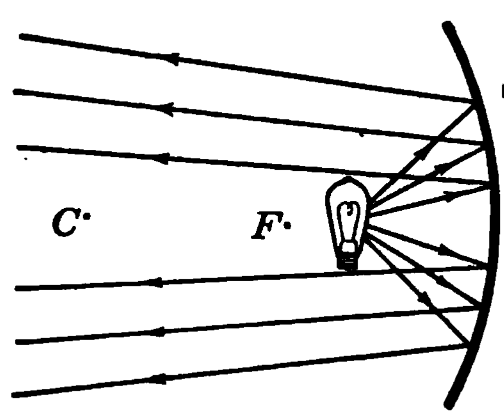



FIG. 300. — Headlights and searchlights.

**330. Spherical Aberration.** It is not strictly true that all parallel rays are reflected to the principal focus. See Fig. 301. The rays of light near the edge of the mirror meet, when reflected, at a point nearer the mirror than the principal focus. This wandering of the focus causes the image to be distorted. The non-focusing of parallel rays at the principal focus is known as *spherical aberration.*

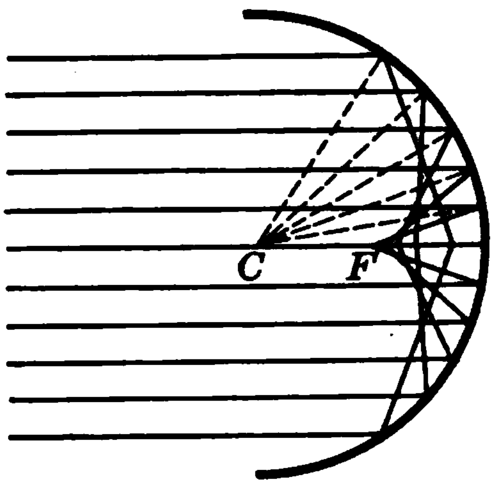



Fig. 301. — Spherical aberration.

Usually mirrors have an aperture of only 10° or 12°; then the distortion is negligible. It is also possible to remedy spherical aberration by using an opaque diaphragm to cut off those rays that would be incident near the edge of the mirror. One of the best methods of preventing spherical aberration is to use a mirror whose surface is not part of a sphere, but has the curve of the parabola. See Fig. 302.

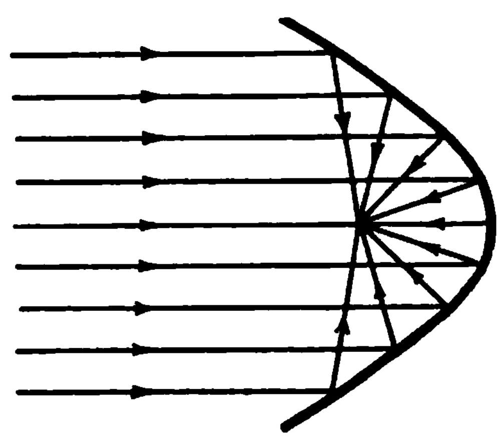


Fig. 302. — Parabolic mirror.

**331. Relative Size of Object and Image.** The relative size of the object and image depends upon their respective distances from the center of curvature, or from the mirror itself. It is very easy to prove that the triangles $CAD$ and $CA'N$ are similar, Fig. 297. Then, $AD : A'N = CD : CN$. Now $AD$ corresponds to the size of the object, which we may call $S_0$; $A'N$ corresponds to the size of the image $S_1$; $CD$ is the distance of the object from the center of curvature, which we may represent by $D_0$; and we may use $D_1$ to represent $CN$, which is the distance of the image from the center of curvature. By substituting these values, we have the following equation:

$$S_0 : S_1 = D_0 : D_1.$$

When any three of these quantities are known the fourth may be computed easily.

The following formula shows the relation of $D_0$ and $D_1$ to the focal length $F$:

$$\frac{1}{D_0} + \frac{1}{D_1} = \frac{1}{F}.$$

This formula may be used in all cases governing spherical mirrors. If the answer is a negative quantity, the image is virtual.

## SUMMARY

The angles of incidence and reflection are equal and they lie in the same plane.

Reflection from a polished surface is regular; from a rough surface, it is irregular or diffused.

Mirrors are plane or spherical; spherical mirrors may be concave or convex.

Images are real or virtual; a real image is inverted and can be thrown upon a screen. Virtual images are erect; they cannot be thrown upon a screen.

Images formed by plane mirrors are erect, virtual, the same size as the object, and as far behind the mirror as the object is in front.

A focus is a point where rays of light meet. Rays parallel to the principal axis are reflected to a point on the principal axis, midway between the center of curvature and the vertex. This point is the principal focus. Its distance from the vertex is the principal focal length. It equals half the radius of curvature.

In concave mirrors the image is a point when the object is at an infinite distance. As the object approaches the mirror, the real image formed increases in size, becoming equal to the object at the center of curvature, and infinitely large at the principal focus. If the object is brought nearer the mirror than the principal focus, the image becomes virtual.

The images formed by convex mirrors are erect, virtual, and smaller than the object.

Spherical aberration is the deviation from the principal focus of those rays of light that are incident near the edge of the mirror. It may be remedied by using a diaphragm, or by having the mirror shaped like a parabola.

## QUESTIONS AND PROBLEMS

1. Why can we look at the image of the sun in the water at noon, but not in the afternoon when it is low on the horizon?

2. Given two plane mirrors, draw a diagram to show how a person on the north side of a house could use them to see a person on the south side.

3. Explain how a too glaring headlight may be remedied by using ground glass.

4. The maximum candle power of the tungsten lamp is horizontal. State two practical ways by which this defect may be remedied.

5. If a man runs toward a plane mirror at the rate of 20 ft. per second, how fast does he approach his image?

6. Given a room 20 ft. square. For general illumination, which would be better, an 80 C.P. lamp placed in the center or four 20 C.P. lamps, one four feet from each corner? Give two reasons for your answer.

7. An object is 4 ft. from a concave mirror whose focal length is 9 in. How far away is the image? If the object is 2 ft. high, what is the height of the image?

8. An object is 8 in. from a concave mirror of focal length 12 in. Find the distance of the image. How many times is the object magnified?

9. A convex mirror is often used on automobiles so the driver can see cars approaching from the rear. What advantage has it over a plane mirror? Are there any disadvantages?

10. Why is the image formed by the bowl of a silver spoon distorted?

11. Lay a plain gold ring on a sheet of white paper. Note the shape of the image that is produced. How does this image, which is called the "caustic by reflection," illustrate spherical aberration? Compare the image with that formed by the inside surface of a glass of water resting on a white tablecloth when the light is strong.

*Suggested Topic.* Diffused Lighting.

## CHAPTER 18

# LIGHT — REFRACTION

**332. Refraction.** A teaspoon in a glass of water appears to be bent or broken at the surface. Fishes appear to be higher in water than they really are, thus making it difficult to shoot or spear them. It is also well known that water is deeper than it appears. If we look into a tall glass cylinder full of clear water and put a finger on the outside of the jar where the bottom appears to be, we find that it is only about three fourths of the way down.

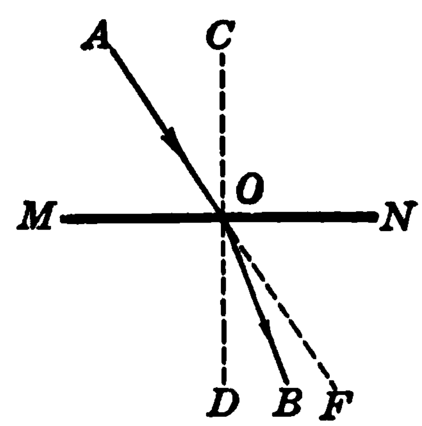


FIG. 303. — Refraction of light.

The bending of a ray of light out of its course as it passes obliquely from one medium into another of different optical density is called *refraction*. In Fig. 303, suppose we let $MN$ represent the surface of a body of water, and $AO$ a ray of light incident upon the water at point $O$. Instead of continuing in its course along the line $OF$ as it passes from the air into the water, it is bent out of its course and takes the path $OB$. The angle $AOC$ is the *angle of incidence*. Angle $DOB$, which is the angle that the refracted ray makes with the normal, is the *angle of refraction*. The angle $BOF$ is the *angle of deviation*.

**333. Cause of Refraction.** Suppose we have five men marching abreast over a hard road. See Fig. 304. Their line of march, $AB$, carries them over a strip of marshy ground where their speed is retarded. The man at $R$ enters the marsh land first and is the first to be retarded. Since

the others continue at the same speed as before, the line of march now takes the direction $BC$. In the marshy ground all are equally retarded until the man $R$ reaches harder ground and his speed increases. The line of march now takes the direction $CD$. The student will observe that as the speed decreases the line bends toward the perpendicular. An increase of speed on entering a new medium causes the line to bend away from the normal. It is evident that if the line of march were along the perpendicular, all would enter the marshy ground at once; they would therefore all be retarded at the same time and the line of march would not be bent. Since a light ray has some thickness, the edge which is first incident upon a medium in which its speed is decreased is the first to be retarded and bent from its course. Light rays incident upon a different medium at an angle of 90° are not refracted.

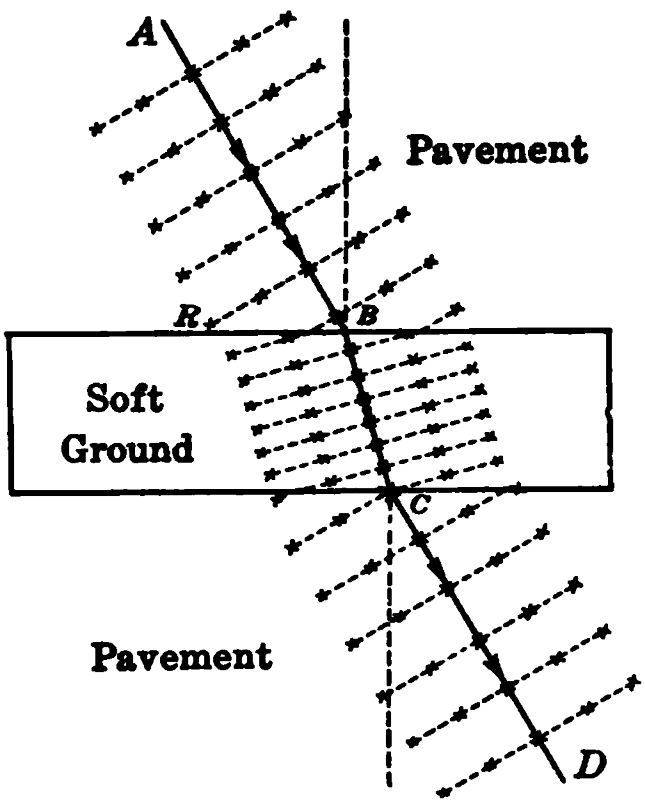


FIG. 304. — Cause of refraction.

**334. Laws of Refraction.** (1) *When a ray of light passes obliquely from a medium of lesser to one of greater optical density, it is bent toward the perpendicular.* As it enters a medium of greater optical density its speed is reduced.

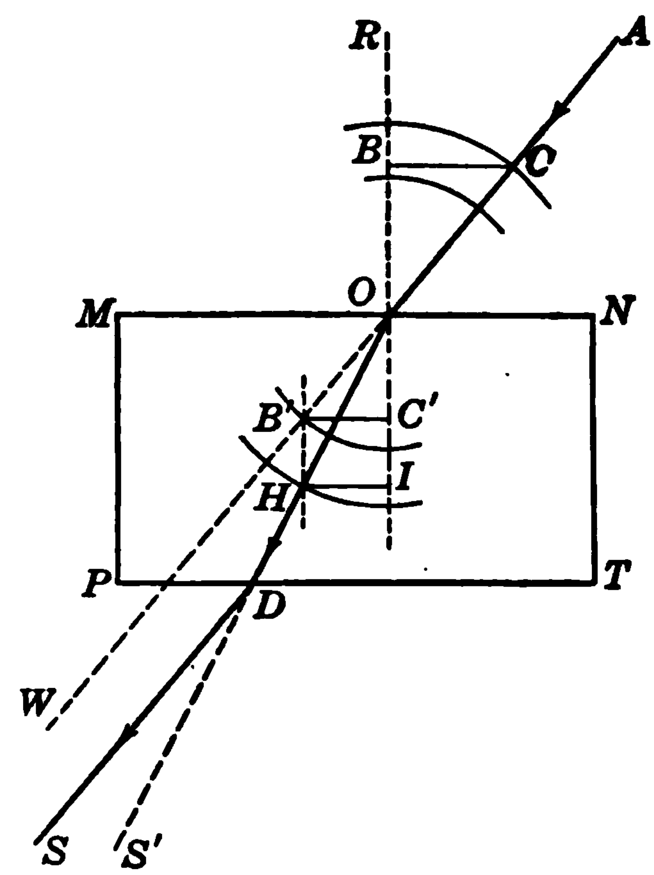


FIG. 305. — Path of ray through a glass plate.

Conversely, *a ray of light passing obliquely from a denser to a rarer medium is bent from the perpendicular to the surface.* As the light passes from the denser to the rarer medium its speed is increased. (2) *The angles of incidence and refraction lie in the same plane.* (3) *The index of refraction is constant for any two media, no matter what the angle of incidence.* Fig. 305 shows the path a ray of light $AO$ takes as it passes obliquely through a piece of plate glass $MNPT$. It is refracted toward the perpendicular as it enters the glass and from the perpendicular upon leaving. By using $O$ as a center and describing arcs having radii of the same ratio as the index of refraction from glass to air, we may construct the lines $BC$ and $HI$ which have a like ratio. The line $OH$ thus represents the refracted ray. The path of a ray of light $AO$ through a prism is shown in Fig. 306.

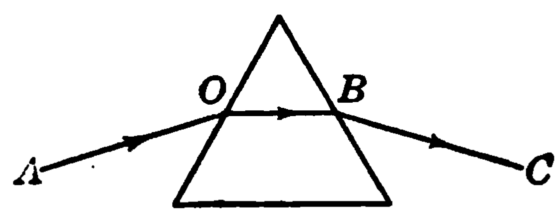


FIG. 306. — Path of ray through prism.

**335. Index of Refraction.** *The index of refraction for any substance is the ratio of the speed of light in air to its speed in that substance.* The speed of light in ordinary glass is about 124,000 miles per second. Then the index of refraction for glass equals $\frac{\text{speed in air}}{\text{speed in glass}}$. The value is $\frac{3}{2}$, or 1.5. Since the speed of light in water is only three fourths as great as in air, the index of refraction of water is $\frac{4}{3}$, or 1.333. The index of refraction of a few substances is given in the following table:

| | | | | | |
|---|---|---|---|---|---|
| Alcohol . . . | 1.36 | Diamond . . | 2.47 | Olive oil . . | 1.47 |
| Canada balsam | 1.52 | Glass, crown . | 1.52 | Opal . . . | 1.45 |
| Cotton seed oil | 1.47 | Glass, flint | 1.54–1.94 | Water . . . | 1.33 |
| Carbon disulphide | 1.62 | | | | |

**336. Applications.** Since transparent substances have a constant index of refraction, the measurement of the index

furnishes a convenient method for their identification. An instrument, called a *refractometer*, has been so constructed that the index can be measured quickly and accurately. Butter fat and oleomargarine have different indices of refraction. This difference furnishes one of the tests used to distinguish butter from oleomargarine. The exceedingly high index of refraction of the diamond furnishes an excellent method of identifying it. Other gems may be identified by their refractive index.

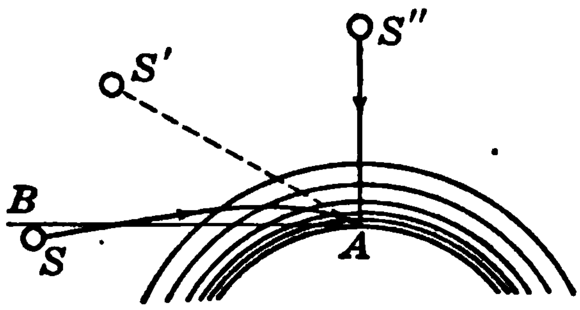



Fig. 307. — Ray through atmosphere.

**337. Atmospheric Refraction.** Light is refracted in passing from ether into the air. Since the atmosphere is denser near the surface of the earth, a ray of light coming from a celestial body like the sun follows a path similar to the curve shown in Fig. 307. The refraction is gradual, instead of one distinct bend at the surface of the medium. $S$ is the true position of the setting sun just below the horizon $AB$. On account of refraction the sun appears to be at $S'$, about one diameter higher than it really is. Since the index of refraction from ether to air is only 1.00029, the diagram is greatly exaggerated. At noon we see the sun in its true position. We see the stars in their true position only when they are at the zenith.

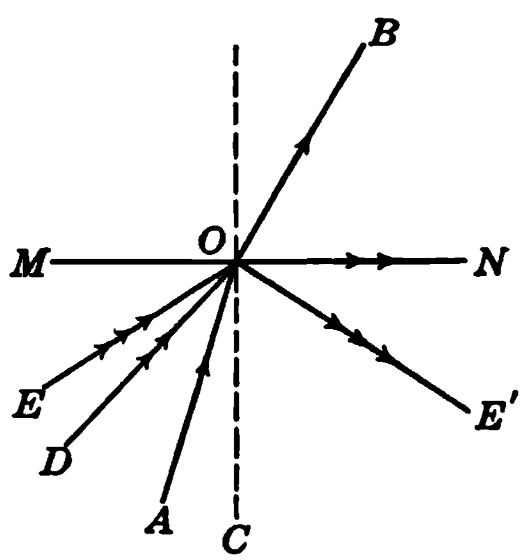



Fig. 308. — Critical angle.

**338. Critical Angle and Total Reflection.** When a ray of light travels from a denser to a rarer medium, it is bent from the perpendicular. In Fig. 308, suppose $AO$ is a ray of light passing from water to air, $MN$ representing the surface between the two media. The ray is refracted along $OB$. If we gradually make the angle of incidence greater,

a point will finally be reached where the refracted ray does not enter the air at all but takes the direction $ON$, coincident with the surface. *That special angle of incidence at which the refracted ray makes an angle of 90° with the normal is called the critical angle.* The angle $DOC$ is the critical angle. If the angle of incidence is made still larger, as $EOC$ for example, then the ray of light is reflected, following the law of reflection. This is *total reflection;* it occurs whenever the angle of incidence exceeds the critical angle. The critical angle for water is 48.5°; for crown glass it is 42°; and for the diamond only 24°. The diamond is the most brilliant of gems. All the light that enters it except within a narrow cone of 48° undergoes total reflection. By setting it in platinum, which is also a good reflector, its brilliancy is enhanced.

**339. Applications of Total Reflection.** We have just learned that the brilliance of the diamond is largely due to total reflection. Cut-glass is made from glass having a high index of refraction in order to increase the amount of light it reflects. When a ray of light enters a right-angle glass prism like that shown in Fig. 309, it is totally reflected. The periscope of a submarine has two such prisms. The observer at $D$ sees objects along the line $AB$. The light rays are reflected down the tube by the first prism. The second prism again changes the direction by total reflection. The right-angle prism is more efficient as a reflector than a mirror would be if set in the same position. In the Zeiss binocular, a very good field glass, such prisms not only give a wider range of vision, but they also reinvert the image, making it erect. The reflecting telescope, and the range-finder used on battleships, also make use of total reflecting prisms.

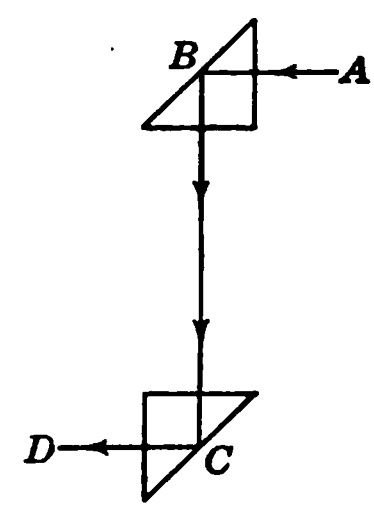



FIG. 309. — Total reflecting prism. Periscope principle.

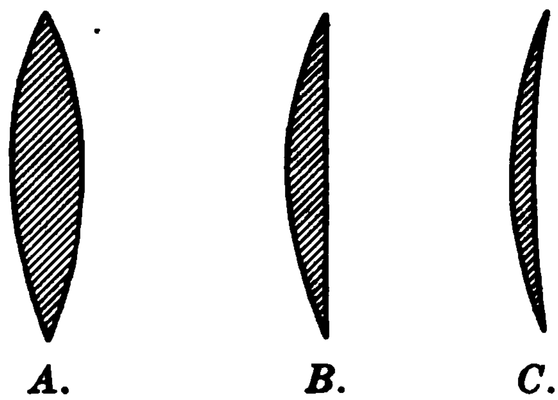



FIG. 310. — Converging lenses. *A*. Double-convex. *B*. Plano-convex. *C*. Concavo-convex.

**340. Lenses.** A lens may be defined as a portion of transparent substance bounded by two curved surfaces, or by one curved and one plane surface. Lenses are nearly always made of glass. Lenses are of two kinds: (1) convex, or converging lenses, which are always thicker in the middle than at the edges — three types of such lenses are shown in Fig. 310; (2) concave, or diverging lenses, which are thinner at the middle than at the edges. Fig. 311 shows three types of concave lenses. Convex lenses cause parallel rays of light to converge to a point or focus, Fig. 312 *A*. If rays of light are already converging, their convergence is increased, so that they focus more quickly. When diverging pencils of light pass through a convex lens, their divergence is decreased. Concave lenses produce the opposite effect. See Fig. 312 *B*. Parallel rays are made diverging; converging pencils have their convergence diminished; diverging pencils have their divergence increased.

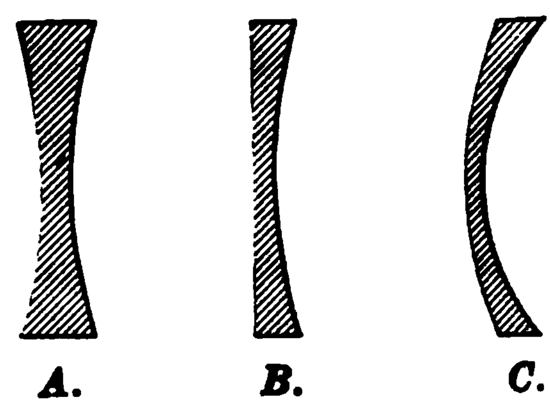



FIG. 311. — Diverging lenses. *A*. Double-concave. *B*. Plano-concave. *C*. Convexo-concave.

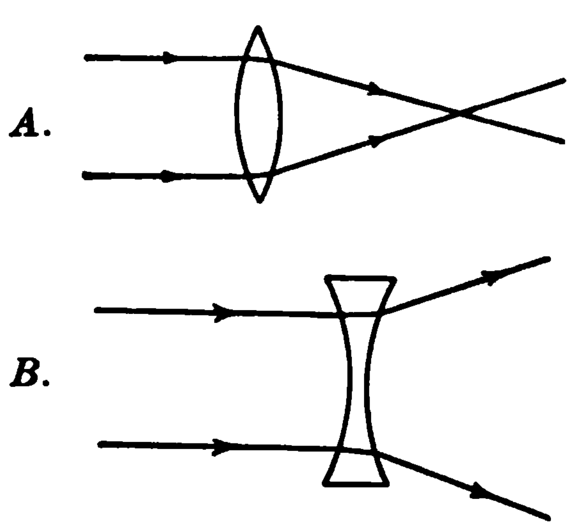



FIG. 312. — *A*. Effect of convex lenses. *B*. Effect of concave lenses.

**341. Definition of Terms.** In most lenses there are two centers of curvature, $CC'$, Fig. 313. The principal axis joins them. *In lenses the secondary axes pass through the optical center of the lens;* the optical center $O$ practically coincides with the geo-

metric center. Rays of light passing through the optical center are *not* refracted. The principal focus is the same by definition as for spherical mirrors, but for a double convex lens of ordinary crown glass it nearly coincides with the center of curvature. Therefore the principal focal length and the radius are approximately equal. A ray of light, $AB$, parallel to the principal axis, is refracted and passes through the principal focus. The thicker the lens, the shorter the focal length becomes.

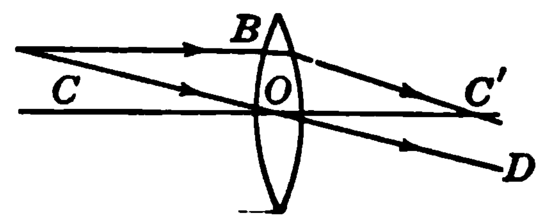


FIG. 313. — Terms defined.

**342. Images Formed by Lenses.** Convex lenses form images in almost the same manner as concave mirrors; concave lenses are analogous to convex mirrors in the manner in which they form images. The student must keep in mind several differences between lenses and mirrors: (1) Secondary axes of lenses pass through the optical center and not through the center of curvature. In Fig. 313 the line $AD$ is a secondary axis. (2) The principal focus is at or near the center of curvature; the focal length is practically equal to the radius, whereas in mirrors it is equal to half the radius. (3) Since the image is formed by rays of light that pass through the lens, a real image is formed on the opposite side of the lens from the object, just the reverse from mirrors. Virtual images formed by lenses appear to be on the same side of the lens as the object. In constructing images formed by lenses, we draw two lines from each point just as we did in the case of mirrors. One of these lines may be the secondary axis; the other a ray parallel to the principal axis which passes through the principal focus after it is refracted by the lens. The image of $A$ in Fig. 313 will be formed beyond the lens where the ray $AB$, refracted along the line $BC'$, meets the secondary axis $AD$.

**343. Images by Convex Lenses.** CASE 1. *When the object is at an infinite distance, the image is a point at the principal*

*focus.* The focal length of a lens may be found by focusing the sun's rays on a white screen and then measuring the distance from the lens to the screen. The optical disc of Fig. 314 shows how parallel rays meet at the principal focus.

Fig. 314. — Refraction of parallel rays by convex lens.

Case 2. *When the object is at a finite distance more than twice the focal length of the lens, the image is smaller, inverted, and real.* The image will be distant more than once and less than twice the focal length of the lens. Fig. 315 shows how the light is focused to form the image $A'B'$.

Case 3. *When the object is at a point twice the focal length of the lens, the image is the same size as the object, inverted, real, and at a distance equal to twice the focal length*, Fig. 316.

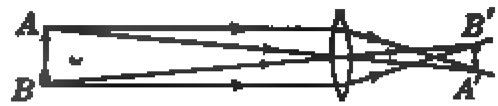


Fig. 315. — Object at finite distance. Case 2.

Case 4. *When the object is distant more than once, but less than twice the focal length, the image is enlarged, inverted, real, and distant more than twice the focal length from the lens.* By reference to Fig. 317 we see that this case is the converse of Case 2.

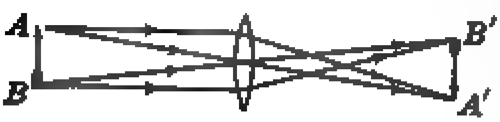


Fig. 316. — Object distant twice focal length. Case 3.

Case 5. *When the object is at the principal focus, the rays of light are parallel as they leave the lens and no image is formed.* Practical use of this fact may be made in lighthouses by putting the light at the principal focus.

Case 6. *When the object is nearer the lens than the principal focus, the image is enlarged,*

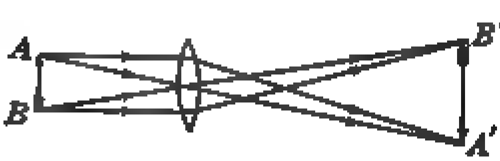


Fig. 317. — Object between $2F$ and $F$. Case 4.

*erect, virtual, and on the same side of the lens as the object.* The rays of light are diverging as they leave the lens. They meet behind the object to form an apparent image.

Just as in convex mirrors, *the images formed by concave lenses are smaller, erect, and virtual.* See Fig. 318.

Fig. 318. — Refraction of parallel rays by concave lens.

**344. Spherical Aberration.** Parallel rays of light which are incident near the edge of a lens do not all meet at the principal focus, Fig. 319. Just as in the case of mirrors, such spherical aberration may be remedied by using a diaphragm to cut off the rays which strike near the edge of the lens, or by grinding the lens so that its surface has the shape of a parabola. A lens corrected for spherical aberration so the lens can be used with the diaphragm open is known as a "high-speed" lens. Pictures taken with a kodak have much better definition if the diaphragm is nearly closed during the exposure so that the rays of light passing through the center of the lens are used to produce the image.

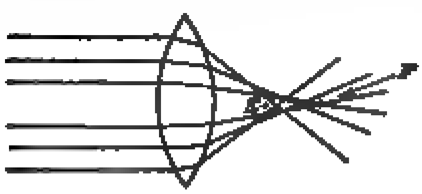


Fig. 319. — Spherical aberration.

**345. Size of Image and Its Distance from the Lens.** The same formulas are used to determine the size and distance of the images formed by lenses as in the case of mirrors. The size may be found by the following formula:

$$S_o : S_i = D_o : D_i$$

For showing the relations between the distances of the object and image and the focal length, we use the following formula:

$$\frac{1}{D_0}+\frac{1}{D_1}=\frac{1}{F}.$$

If the result is a negative quantity, the image is virtual.

## SUMMARY

Refraction is the bending of a ray of light out of its course as it passes obliquely from one medium into another of different optical density. When passing into a more highly refractive medium, it is bent toward the perpendicular and conversely.

The index of refraction of any substance is the ratio of the speed of light in air to its speed in that substance.

That especial angle of incidence at which the refracted ray is perpendicular to the normal is called the critical angle. Total reflection occurs when the angle of incidence exceeds the critical angle.

In the manner in which they form images, convex lenses are analogous to concave mirrors; concave lenses are analogous to convex mirrors.

Spherical aberration, which occurs in lenses as well as in mirrors, may be remedied by the use of a diaphragm.

## QUESTIONS AND PROBLEMS

1. Give two reasons why the sun is visible after it sinks below the horizon. Is it visible before it rises above the horizon?

2. In making microscopic slides Canada balsam is used to cement the cover glass to the slide. Give a good reason why Canada balsam is used.

3. Flint glass is used in making cut glass. What advantage has it over crown glass?

4. What effect would immersion in water have upon the focal length of a convex lens?

5. How fast does light travel in the diamond? What is its speed in crown glass? in flint glass? (Index of refraction, 1.65.)

6. A candle is 8 ft. from a double convex lens of 9 in. focal length. How far away is the image and what is its size as compared with the object?

7. An object placed 80 cm. in front of a double convex lens forms a distinct image on a screen 25 cm. on the other side of the lens. What is the focal length of the lens?

8. An object is 30 cm. in front of a double convex lens whose focal length is 50 cm. How far away is the image formed? How does it compare in size with the object?

9. Draw a diagram to show how a dark lantern must be constructed to throw a beam of light in one direction only.

10. Objects are practically invisible when immersed in a liquid that has the same index of refraction. How can carbon disulphide be used to distinguish between real diamonds and "paste" diamonds, which are made of flint glass?

*Suggested Topics.* Testing Gems. Mirage.

## CHAPTER 19

# LIGHT — OPTICAL INSTRUMENTS

**346. Optical Instruments.** Although mirrors may be used in certain types of optical instruments, yet a single lens or a combination of lenses is more often used to form images. Such instruments may be used to magnify an object, to make a distant object seem nearer, to project an image on a screen, or to distribute light properly.

**347. The Eye.** In many respects the eye is the most perfect optical instrument. It has three coats: (1) The white outer coat is tough and firm; hence it not only preserves the spherical shape, but it is also a source of protection. (2) The middle coat is black. It is interesting to note that nearly all optical instruments have the interior blackened to absorb stray light waves that might be reflected from the walls, thereby blurring the image. (3) The inner coat covers the back part of the eyeball only. It is called the retina. See Fig. 320. On the *retina*, as shown at $R$, the nerves of the eye are spread out, thus making a sensitive screen. The crystalline lens $L$ forms a real, inverted image on the retina. The iris $I$ serves as a diaphragm to cut off the rays of light from the edge of the lens. The opening in the iris is called the pupil. The iris also regulates the amount of light that enters the eye. In a dark room the opening is large

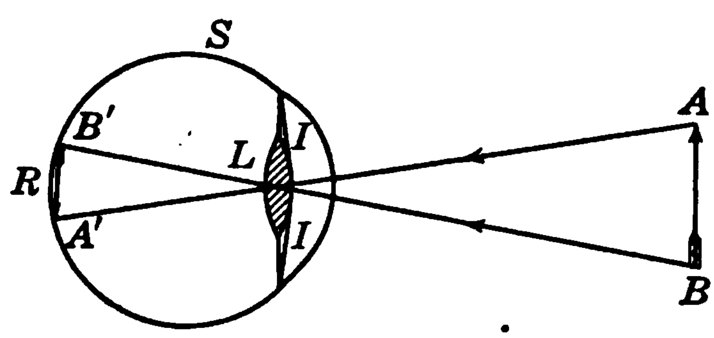


FIG. 320. — Structure of eye.

to admit more light, but in bright sunshine the pupil is reduced until it is about the size of a pin-head. The lens is supported by a small muscle which may contract and change the shape of the lens. When it makes the lens more convex, near-by objects are in proper "focus" on the retina. In the normal eye the lens can be made convex enough to see clearly objects as close as 10 in., or 25 cm. When we read for a long time with the book at this distance, the muscle which keeps the lens properly "focused" becomes tired. When the muscle relaxes, the lens becomes flatter and more distant objects are then in "focus."

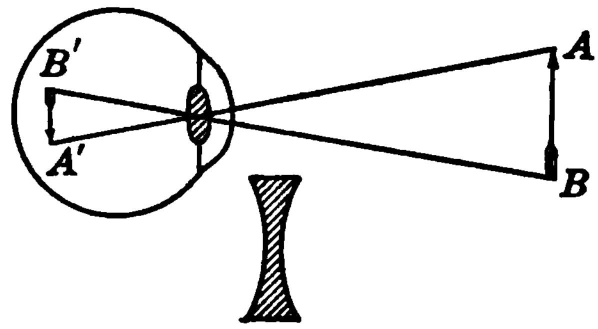



FIG. 321. — Near-sightedness remedied by concave glasses.

**348. Defects of the Eye.** We have seen that the normal eye is "self-focusing," since the crystalline lens is changed in shape so that the image falls on the retina, whether the object is near by or quite distant. If the eye-ball is too much elongated or the lens too convex, this power of accommodation will not occur, but the image will be formed in front of the retina. Only when the object is brought very close will such an eye give distinct vision. See Fig. 321. The remedy for *near-sightedness* consists in wearing glasses which partially neutralize the convexity of the crystalline lens. Glasses with concave lenses are used. If the eye-ball is too short or the lens too flat, *far-sightedness* will result. See Fig. 322. It may be remedied by wearing glasses with convex lenses. Glasses with double lenses, bi-focals, are used extensively so that a person may see near objects clearly with one set of lenses, and use the other set when look-

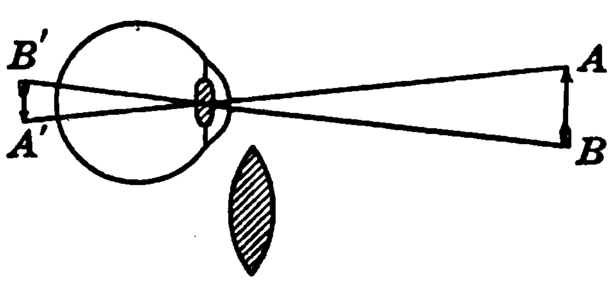



FIG. 322. — Far-sightedness remedied by convex glasses.

ing at distant objects. *Astigmatism* occurs when the lens or the cornea does not have a perfectly curved surface. All parts of the object are not in focus at the same time. In a case of astigmatism some of the lines of Fig. 323 will appear distinct while those on the opposite side of the figure may be blurred. Glasses having lenses especially ground to counteract these irregularities are used to remedy this defect. Some eye-glasses are made with flat lenses; others have meniscus lenses. See Fig. 324. A flat lens will focus properly only when the wearer looks through the center of the lens. If he looks through the edges of the lens, a blurred image is formed. With the meniscus lens the range of distinct vision is much larger. It is unnecessary for the wearer to turn his head to see clearly objects which are at an angle. See Figs. 325 and 326.

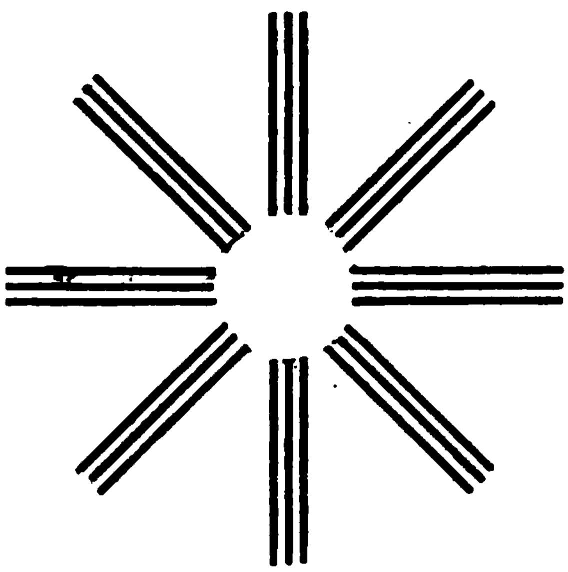


FIG. 323. — Astigmatism.

**349. Apparent Size of an Object.** An object near the eye appears larger than when farther distant. Fig. 327 shows that the image of $AB$ which is formed on the retina is larger than the image of $A'B'$. The *visual angle* $ACB$ is larger than the angle $A'CB'$. Hence $AB$ appears larger than $A'B'$. A man looks larger a few feet away than he does when he is 100 yards distant. If we know the size of an object, we may judge its distance by the size of the image formed on the retina.

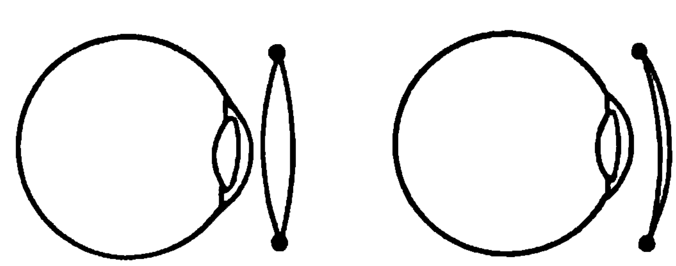


FIG. 324. — Flat and meniscus lenses.

Let the student try to stick a pin in the center of a letter $O$ on a printed page held at arm's length, first with one eye closed and then with both eyes open. He will thus learn

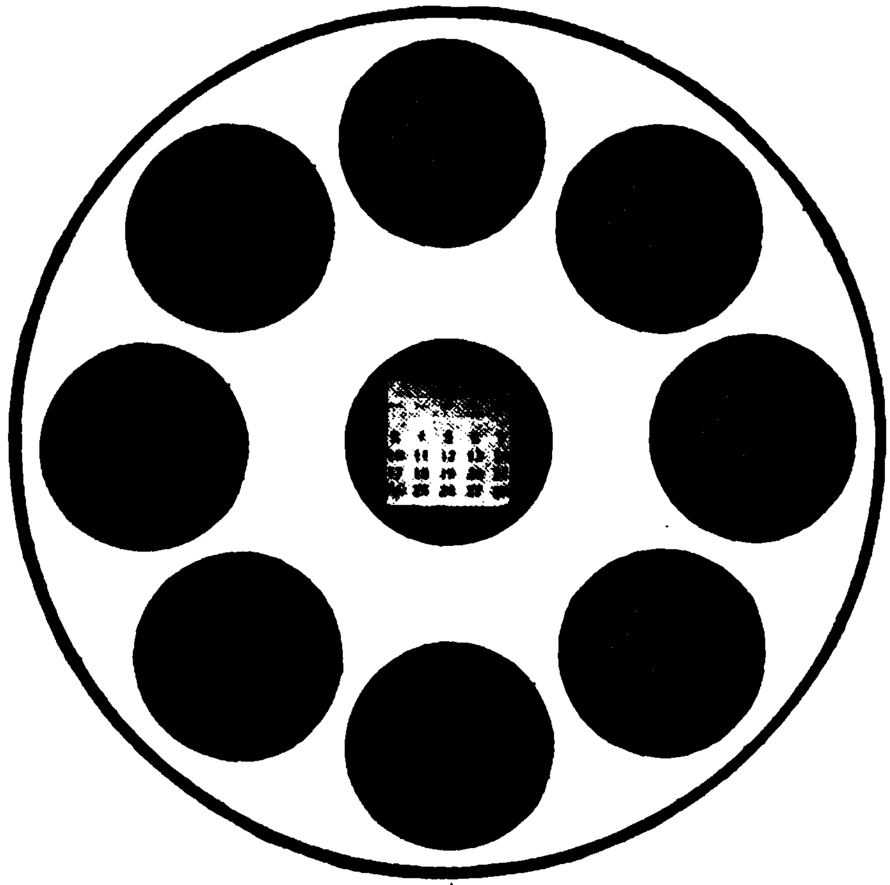


FIG. 325. — Effect of flat lenses.

that the size of the image alone does not enable him to judge distance very accurately. When both eyes are used, one has the advantage of an estimate formed by the amount of effort required to focus both eyes on the object. In Fig. 328, the distance between the eyes, $AB$, forms a known base line, from which we learn to estimate the distance $CD$ by the angles $CAD$ and $CBD$. The nearer the object is brought to the eye, the smaller these angles become. We estimate distance in such cases by the muscular effort required to roll the eyes inward until both are focused on the object.

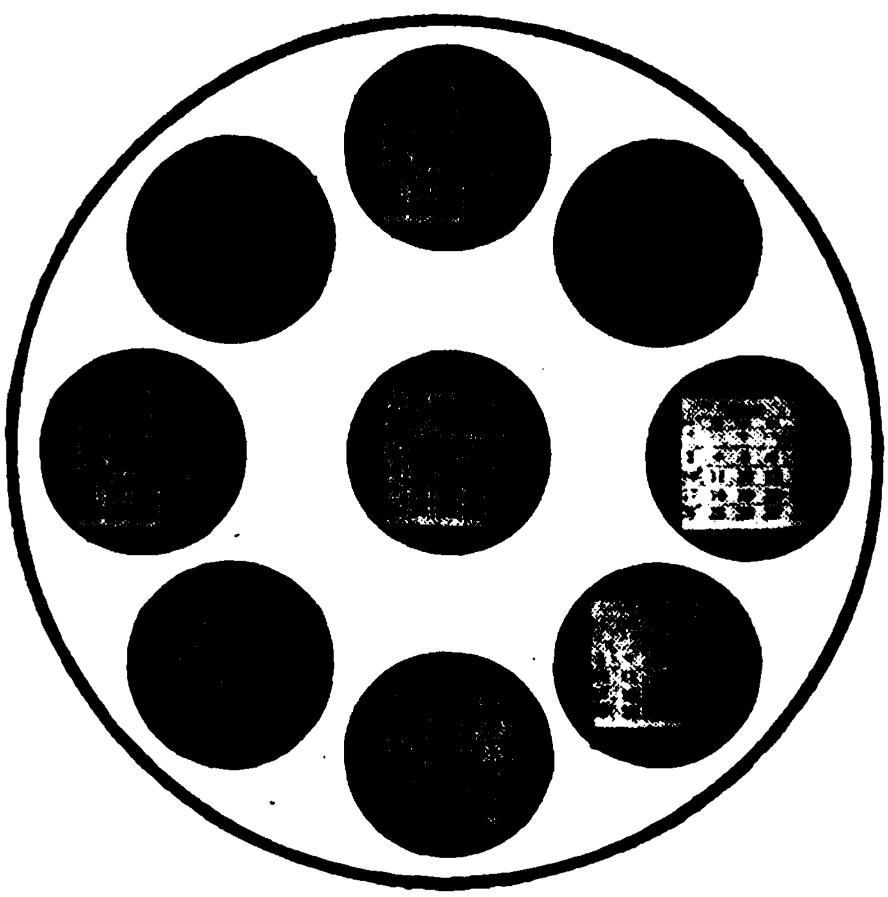


FIG. 326. — Effect of meniscus lenses.

Battleships find the range at sea by using for the base line $AB$ a tube 12 to 15 ft. long. At each end of the tube there is a total reflecting prism. These prisms are focused on the distant object. The angles are accurately measured and $CD$ computed by

trigonometry. Such range-finders are generally calibrated to read distance directly.

**350. The Simple Magnifier.** We have learned that the size of the image formed on the retina increases as the object is brought nearer the eye, because the visual angle is increased. If the object is brought nearer than 10 in., however, the lens of the eye cannot be made sufficiently convex to form a clear image. The distance, 10 in. or 25 cm., is the least distance for clear vision with the normal eye. A simple magnifier may be used to assist the lens of the eye in forming an image when the object is very close. A double convex lens of rather short focal length is generally used. The lens is held a little nearer the object than its focal length and the eye is placed close to the lens. See Fig. 329. In this way an enlarged, erect, virtual image of the object is formed. Since the object is so near the principal focus, the *approximate* magnifying power of a lens is obtained by dividing 10 in., or 25 cm., the least distance for distinct vision, by the focal length of the lens.

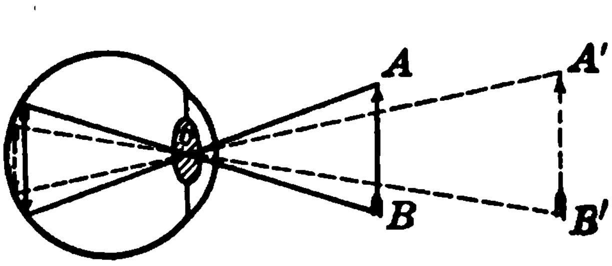


FIG. 327. — Size of object.

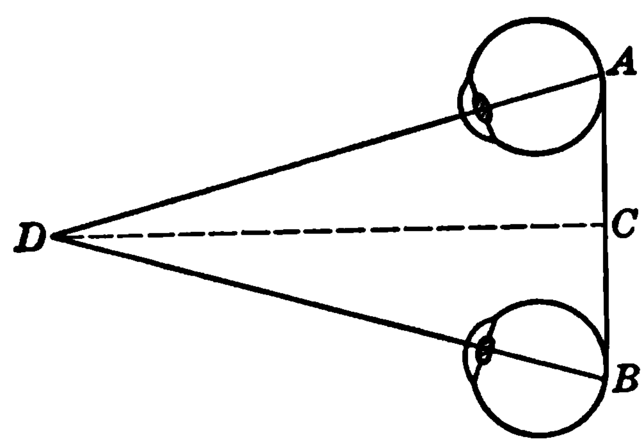


FIG. 328. — Judgment of distance.

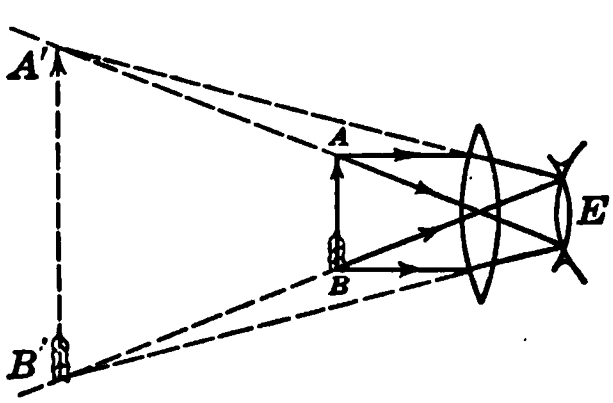


FIG. 329. — Simple magnifier.

**351. The Compound Microscope.** The invention of the compound microscope by Janssen marked the beginning of a new era in the study of plant and animal physiology. Without the microscope nothing would now be known concerning

the action of pathogenic bacteria in producing contagious diseases. In its simplest form the compound microscope has two converging lenses, the eye-piece and the objective, mounted at opposite ends of a brass tube about 200 mm. long. The objective $O$, brought to a distance a little greater than its focal length from the object, forms a real, inverted, enlarged image which is again magnified by the eye-piece $E$, acting as a simple magnifier. See Fig. 330. The magnifying power of the objective equals approximately the length of the tube $L$ divided by the focal length of the objective $F$. Since the magnifying power of the eye-piece equals $\frac{25 \text{ cm.}}{f}$, in which $f$ is the focal length of the eye-piece, then the total magnification is the product of both, or $\frac{25\,L}{f\,F}$. Suppose the tube is 16 cm. long, the focal length of the objective is 0.5 cm., and the focal length of the eye-piece is 2.5 cm. The objective magnifies the object 32 diameters and the eye-piece 10 diameters. The total magnification is 320 diameters.

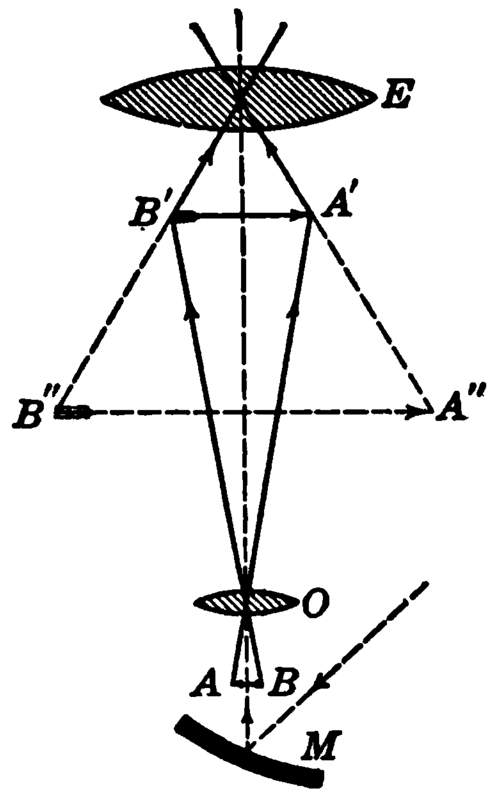


FIG. 330. — Compound microscope.

**352. The Telescope.** The *refracting* telescope is constructed on practically the same principles as the compound microscope. The objective $O$ is very large in diameter to collect more light rays, and it has a very long focal length. The diameter of the objective in the Yerkes telescope is 40 in. and its focal length is over 60 ft. It magnifies 5000 diameters with a 0.5 cm. eye-piece. Since heavenly bodies are so far distant, small, inverted images are formed which are then highly magnified by the eye-piece $E$. The

magnifying power is practically equal to the focal length of the objective $F$ divided by the focal length of the eye-piece $f$, or $\frac{F}{f}$, Fig. 331. In the *reflecting* telescope a large concave mirror is used to collect the light rays. For astronomical observations it matters little if the image is inverted, but in the *terrestrial* telescope of Fig. 332 a third lens $L$ is placed between the objective and the eye-piece to reinvert the image; therefore the observer sees the object in its normal position. Telescopic sights are sometimes used on long-range rifles. Cross threads intersecting at right angles are suspended in the telescope. When the telescope is adjusted so the image is focused on the intersection of these threads, then the object, the center of the objective, and the point of intersection are all in the same straight line. Surveyors use the same kind of a telescope in their "transits" and "levels."

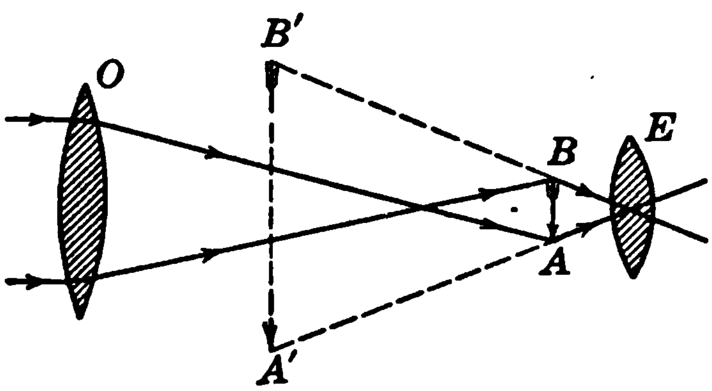



FIG. 331. — Refracting telescope.

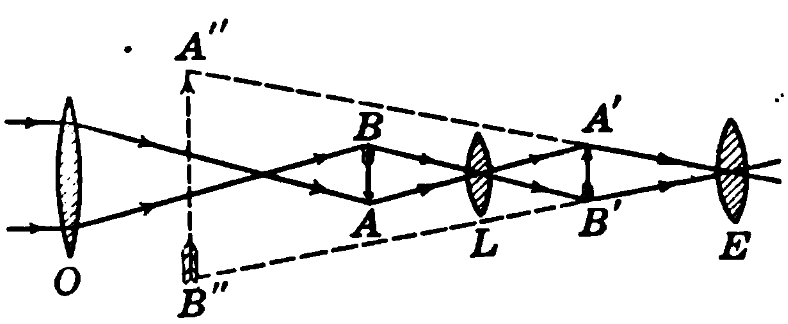



FIG. 332. — Terrestrial telescope.

**353. Opera Glasses.** The opera glass is lighter than the telescope and, having two tubes, it has the advantage of giving binocular vision. The eye-piece has the same focal length as the crystalline lens of the eye, but it is concave; hence it practically neutralizes the lens of the eye. The objective, a lens of larger size and greater focal length, is then virtually substituted for the crystalline lens. Opera glasses usually magnify only 3 or 4 times, the magnifying power being approximately equal to the length of the tube

in inches. The image is erect. In Fig. 333, $E$ is the eyepiece and $O$ the objective. Some binoculars are made with total reflecting prisms so placed that they increase the visual angle thus enabling the user to scan a broader field without changing his position. See Fig. 334.

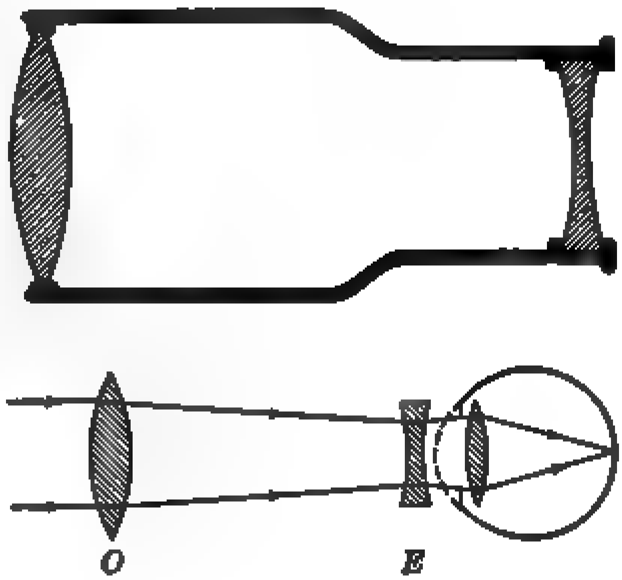



FIG. 333. — Opera glasses.

**354. The Camera.** The camera, Fig. 335, consists of a box, blackened on the inside to absorb stray rays of light, and adjustable in length. At one end is a ground-glass plate, in front of which a sensitive film or plate $S$ is placed to receive the image. At the other end is a convex lens or a combination of lenses $L$. These lenses form a real, inverted image on the sensitive plate.

FIG. 334. — Binoculars. Total reflecting prisms.

The camera is very similar to the eye in its operation. The lens of the camera forms a real, inverted image in the same manner as the lens of the eye. The sensitive plate receives the image in the camera; the retina receives the image formed in the eye. The diaphragm or stop regulates the amount of light that enters the camera just as the iris permits the proper amount of light to enter the eye. There are certain

points of difference. The eye is self-focusing, while in the camera the lens must be moved nearer to the sensitive plate or farther away, depending entirely upon the distance of the object. The camera gives us a picture of all the details of the object, while some of the details of an image formed on the retina are so feebly impressed that they are ignored or forgotten. The photograph gives a picture of an object at a certain instant in a given position, while the mental image received through the eye may be a composite picture of several successive images in different positions. The mental image may also be influenced by former experiences we have had. If our judgment as based upon such experiences is at fault, optical illusions occur. See Fig. 336.

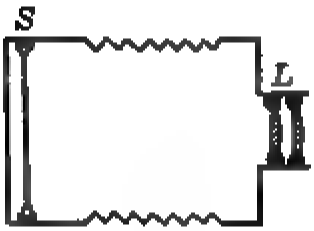


Fig. 335. — Diagram of camera.

Many insects are very hard to see when at rest on twigs or leaves, because they assume the same color as their surroundings. This protective coloration is common among animals that change a brown or tawny coat of summer for one of white in winter. The white stripes and patches of the tiger, zebra, and giraffe resemble spots or streaks of sunlight passing through foliage or reflected by leaves.

The art of mimicry and protective resemblance was much practiced during the World War. Fig. 337 shows a tank that was covered with "dazzle paint." By similar methods of *camouflage* many ships escaped the enemy submarines.

Fig. 336. — Optical illusions.

**355. Anastigmat and Rectilinear Lenses.** When ordinary lenses are used with the diaphragm well opened, the image produced is generally sharp and well defined at the center, but it is

Fig. 337. — Camouflaged tank. Hold picture at distance of 4 ft. and notice loss of detail.

"streaky" or blurred near the edges. This defect of lenses is known as astigmatism. By using a combination of lenses of suitable refractive indices and focal lengths, like that shown in Fig. 338, it is possible to make an *anastigmat* lens which gives good definition over a wide area. At the same time the lens combination must be corrected for spherical and chromatic aberration.

Fig. 338. — Anastigmat lenses

Lenses that can be used with a large aperture are fast, and they can be used for high-speed work. The *effective aperture* of a lens is equal to the diameter of the lens as it appears when seen through the front lens. The speed of a lens depends upon the ratio of its effective aperture to its focal length, or upon its *relative aperture.* In an $F$-4 lens, the focal length is 4 times the effective aperture. Such a lens is 4 times as fast as an

*F*–8 lens, and 16 times as fast as an *F*–16 lens. The speed ratios are proportional to the squares of the relative apertures.

If a plano-convex lens is placed in a camera so the flat side is toward the object, the image that is formed is distorted so that a square has the appearance shown by the solid lines of Fig. 339 *A*. When the lens is turned so its convex side faces the object, the opposite effect is produced. See Fig. 339 *B*. Distortion is produced by all single lenses, the effect being especially noticeable in pictures of buildings with straight lines. The defect may be remedied by using two lenses with their corresponding curves facing in opposite directions and with the diaphragm between the lenses. Such a combination is called a *rectilinear* (straight-line) lens.

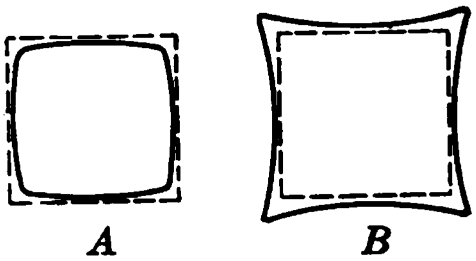



FIG. 339. — Effect of diaphragm upon straight lines.

**356. The Optical Lantern.** In the projection lantern, Fig. 340, an enlarged, inverted image of a transparent slide is thrown upon a screen; the slide is inverted, therefore the image appears erect. The arc lamp is generally used as the source of light. Two plano-convex lenses *LL′* are used as condensers to collect a larger amount of light rays than the slide would otherwise receive. The slide is placed at the position *S*. The objective *O* is a combination of converging lenses which act like a single convex lens. Its distance from the slide is a little greater than its focal length.

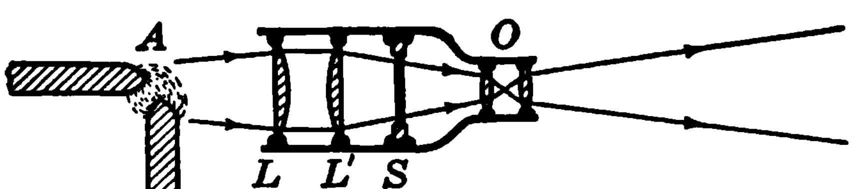



FIG. 340. — Optical lantern.

Moving pictures are projected on a screen in the same manner, a roll of film being used instead of slides. An important physiological effect, the duration of vision, is applied in this case. The image of an object formed on the retina

endures from $\frac{1}{30}$ to $\frac{1}{10}$ of a second after the object is removed. If a second object is introduced before that time has elapsed, a continuous effect is produced. The spokes of a rapidly rotating carriage wheel succeed one another so fast that the wheel appears solid. In preparing a film, from 16 to 50 pictures of a moving object are taken per second. When thrown on a screen, they succeed one another at about the same rate, giving a continuous effect. The film moves rapidly while the shutter is closed, but remains stationary for a short fraction of a second when it is open. Note that the pictures in a strip of film differ slightly.

A motion picture machine is shown in Fig. 342. With cellulose acetate film, which is not so highly inflammable, this machine may be used without being enclosed in a fire-proof compartment.

**357. Lampshades and Illumination.** Daylight is usually well diffused, but for the proper distribution of artificial light, shades or reflectors are essential. In a library or reading room the light should be fairly close and concentrated. For living rooms and assembly halls the illumination is more general.

In the *direct* system of illumination the light shines directly upon the object to be lighted; a rather narrow shade or a concave reflector may be used to concentrate more light upon the object. This is the most economical system of lighting,

FIG. 342. — Safety standard motion picture projector.

but the eyes are sometimes injured by the glare which comes from the light itself or from the reflector. In electric lighting the bulbs are either frosted or made of translucent glass in order to modify the glaring light of the filament. See Fig. 343.

For general illumination the *indirect* or the *semi-indirect* system is often used. With the indirect system the lamps are placed near the ceiling; a large opaque bowl-shaped reflector placed beneath the lamp reflects the light to the ceiling, whence it is diffused to all parts of the room. Fig. 344. If the ceilings are white, an even diffusion of the light

is thus secured and the system is quite efficient. White or light yellow walls and ceilings may reflect as much as 50% of the light they receive. Red, brown, or green walls absorb about 85 or 90% of the light received, and are not suitable for indirect lighting. While the indirect system of lighting is always more costly, yet the light is soft and pleasing and sharp shadows are eliminated.

FIG. 343. — Direct lighting.

In the semi-indirect system of lighting, the lamp is partially inclosed in a translucent globe. Fig. 345. A part of the light is thus reflected to the ceiling and the remainder is diffused directly through the globe. This system is designed to combine the advantages of the direct and the indirect systems. Fig. 346 shows a method of *diffusion* lighting now in common use.

FIG. 344. — Indirect lighting.

FIG. 345. — Semi-indirect lighting.

Much progress

FIG. 346. — Diffusion lighting.

has been made within the last few years in the field of illuminating engineering. The practice of outlining the domes and towers of prominent buildings, or even the buildings themselves, with rows of incandescent lamps has in certain cases been superseded by *flood lighting*. Fig. 347 shows the Woolworth Building at night. The tower is beautifully lighted by a battery of projectors. A single projector used for this type of lighting is shown in Fig. 348. The battery of projectors, Fig. 349, may be used for lighting towers or buildings, or it may find use in lighting construction jobs where night work is necessary.

FIG. 347. — The tower of the Woolworth Building lighted by a battery of projectors. Flood lighting.

## QUESTIONS AND PROBLEMS

1. Why is the image formed by a compound microscope inverted?

2. Why is the interior of optical instruments painted black?

3. In old age the lens of the eye loses the power of accommodation. What kind of glasses are used by old persons as reading glasses?

4. Convexo-concave or concavo-convex lenses (meniscus) are now more often used in spectacles than the flat lenses. What advantages do such meniscus lenses have?

5. Where is the slide placed in an optical lantern with respect to the focal length of the objective?

6. What advantages has the eye over the camera as an optical instrument? What are its disadvantages?

FIG. 348. — Projector for flood lighting.

FIG. 349. — Battery of projectors.

7. Why does the moon appear larger when near the horizon than when it is on the meridian?

8. Prism glass like that shown in Fig. 350 is often used instead of ordinary window glass. What advantage has it? What are its disadvantages?

FIG. 350. — Prism glass.

9. A reading glass has a focal length of 5 in. What is its magnifying power?

10. A camera has a lens whose focal length is 6 in. If the plate is 6.25 in. from the lens when the camera is in focus, how far away is the object? Suppose the object is 6 ft. high by 8 ft. wide, what is the smallest sized plate that can be used to show all the object at the distance found?

11. How is it that owls and cats can see so well at night? What shape has the pupil of a cat's eye when seen at night? When observed in daylight?

12. Name several optical instruments you have used that form real images. Name several that form virtual images.

13. Why do the parallel rails of a railroad track appear to meet at a distance?

14. Draw a diagram to show where a light must be placed with reference to a large double convex lens to produce a spotlight? Where is the light placed with reference to the lens in a lighthouse?

*Suggested Topics.* Ultramicroscope. Astronomical Telescopes. Transit Instruments. Sextant. Opaque Projection. Stereoscopic Vision.

## CHAPTER 20

# LIGHT — COLOR

**358. Dispersion or Analysis of Light.** If we pass a beam of sunlight through a glass prism and let the rays fall on a white screen, a band of colors may be seen. Such a band of colors is called the *solar spectrum;* it shows that white light is composite and may be separated into several colors. The violet light is refracted more in passing through the glass than the other colors, since it has the shortest wave length. The red rays are bent least in passing through the prism. The separation of composite light into several colors is known as *dispersion;* it is generally caused by refraction. Fig. 351 shows the order in which the seven colors of which sunlight is composed appear on the screen.

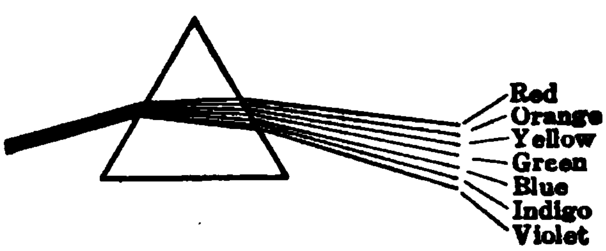


FIG. 351. — Dispersion of light.

**359. Color.** Color bears the same relation to light that pitch does to sound; it depends upon the number of vibrations that reach the eye per second. When an object is heated, the electrically charged particles in its atoms oscillate more rapidly as the temperature increases. Eventually the vibration becomes rapid enough to give out waves to which the eye is sensitive. The first color that the eye can detect is a very dark red; the waves that are capable of producing the sensation of red are 0.00081 mm. long. As the frequency increases other colors are produced in succession until violet, which has the shortest waves that the eye can

perceive, is finally produced. The following table shows the wave lengths of the different colors:

| | | | |
|---|---|---|---|
| Very dark red | 0.00081 mm. | Green . . . . | 0.00052 mm. |
| Red . . . | 0.00065 mm. | Bluish green . . | 0.00050 mm. |
| Reddish orange | 0.00064 mm. | Blue . . . . | 0.00047 mm. |
| Orange . . | 0.00060 mm. | Indigo . . . . | 0.00043 mm. |
| Yellow . . . | 0.00058 mm. | Violet . . . . | 0.00041 mm. |

Extreme limit of visibility . 0.00039 mm.

The table shows that the range of frequencies to which the eye is sensitive is only about one octave. Shorter waves are known, but they do not produce the sensation of light. The frequency of a light wave may be determined by dividing 300,000 kilometers by the wave length.

**360. Color of Objects.** It will be rather difficult for students to think of color as a property of light waves rather than of substances. It is true, however, that the color does not exist in the substance itself, but it depends upon the ability of the substance to reflect light to the eye. When an object reflects all the sunlight it receives, we say that it is white; if it absorbs all the light it receives, it is black. We say that *an opaque object is blue if it reflects blue light to the eye and absorbs all the other colors.* It is very easy to demonstrate these facts. If we put a piece of red paper in the blue portion of the solar spectrum, it will appear nearly black. The red paper can reflect only red rays of light; hence when it receives blue light only, the blue is absorbed and the red paper appears to be black. Artificial lights are apt to be deficient in certain colors, especially the blue and the violet. A ribbon that is blue in sunlight may appear green when examined by candle light. From these observations it seems clear that the color of an object depends: (1) upon the kind of light it receives; and (2) upon its ability to reflect light to the eye. Strictly speaking, color is a property of light waves that depends entirely upon their wave length.

The color of transparent objects depends upon the color of the light waves they transmit. Ordinary window glass transmits all the colors and is colorless. Red glass absorbs all the colors except the red, which it transmits.

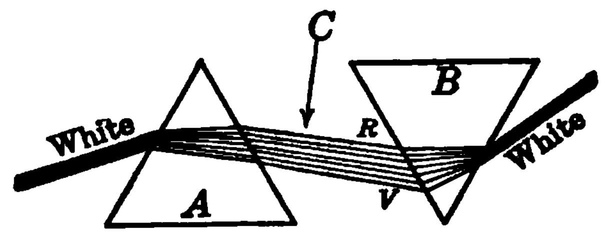


FIG. 352. — Synthesis of light.

**361. Synthesis of Spectral Colors.** If a solar spectrum falls upon a second prism, arranged as in Fig. 352, the colors recombine and produce a single beam of white light. If we rotate rapidly a disc colored as indicated in Fig. 353, the colors will combine to produce white light. The light from one color forms an image on the retina that persists until the other colors have been reflected to the eye in turn. If pure spectral colors are used, they all combine to produce white light.

**362. Complementary Colors.** If we introduce an opaque cardboard into the spectrum of Fig. 352 at *C*, just far enough to cut off the red rays, the other six colors will combine in passing through the second prism to produce green light. Since we get green by subtracting red light from white light, we should be able to combine red and green lights to produce white. This can be done by mixing these two colors with the rotating disc as described in § 361. *Any two colors that combine in this way to produce white light are said to be complementary.* If the blue rays of light are intercepted, yellow light is produced. Hence yellow is the complement of blue.

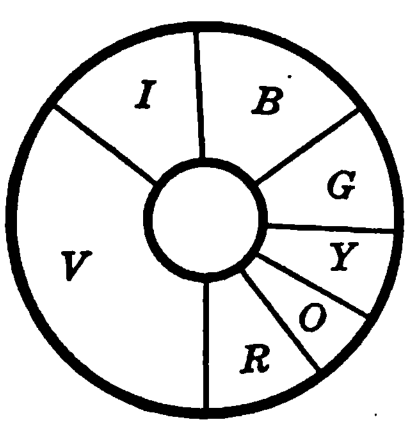


FIG. 353. — Disc for synthesis of light.

White goods acquire a yellow tint after they have been laundered. Since blue is the complement of yellow, "bluing" is used to whiten the wash.

**363. The Three Primary Colors.** Since sunlight is composed of seven colors which cannot be analyzed further,

these colors are sometimes considered elementary colors. We have seen that they can recombine to produce white light.

Experiment shows that white light may also be produced by combining two complementary colors. Three colors, too, have been found from which white light may be obtained, if they are mixed in the proper proportions. These colors are *red*, *green*, and *bluish-violet*. Since it is possible to produce *any* color by blending these three colors in correct proportions, they are called *fundamental colors* or *primary colors*.

**364. Young-Helmholtz Color Theory.** The trichromatic theory of color sensation was first proposed by Dr. Thomas Young and later elaborated by Helmholtz. The theory assumes that the eye is sensitive to the *three primary colors only*. The retina is provided with three sets of nerves, one set which is sensitive to red light, another to green, and a third to bluish-violet. If all the sets of nerves are equally stimulated, we receive the sensation of white. Blackness or darkness is the result of no stimulation. If red wave lengths enter the eye, they stimulate *chiefly* the nerves that produce the sensation of red, but to a lesser degree those nerves that produce the sensations of green and bluish-violet. When yellow light falls upon the retina, both the red and green nerve cells are affected, and the sensation of yellow is produced in the brain.

**365. Color Blindness.** When one or more sets of these nerve cells is lacking in the eye, a person is said to be color-blind. In some cases two sets of nerves are lacking, and in rare cases all three sets. Such persons cannot distinguish certain colors, especially red and green. If all three sets are wanting, the eye is sensitive only to lights and shadows.

This defect in the eye was described by John Dalton and is sometimes known as Daltonism. Color blindness is much more common in men than in women; about 4% of men have this defect, for which there is no remedy. Not more than

one woman in 200 is color-blind. The poet Whittier is said to have patched a green wallpaper in his library with a bright crimson pattern. John Dalton, who was a Quaker, at one time appeared on the streets wearing red stockings; to him they appeared gray. Railroad wrecks have occurred because the engineer was unable to dintinguish red lights from green lights. Men applying for such positions are now carefully examined in order to detect color blindness. To pass the tests, each man must match certain skeins of colored yarn.

**366. Retinal Fatigue.** Suspend a bright red disc on a white background. Let each pupil look intently at the disc for about one minute and then at the white background. A green spot the size of the red disc will be observed. This phenomenon is due to *retinal fatigue.* The retina tires of the red and refuses to be stimulated by it any longer; the other colors reflected from the white surface then combine to produce green, which is the complement of red. If we repeat the experiment using a blue disc, a yellow spot will be seen after the eye tires of blue. Complementary colors are generally harmonizing colors when used for decorative effect.

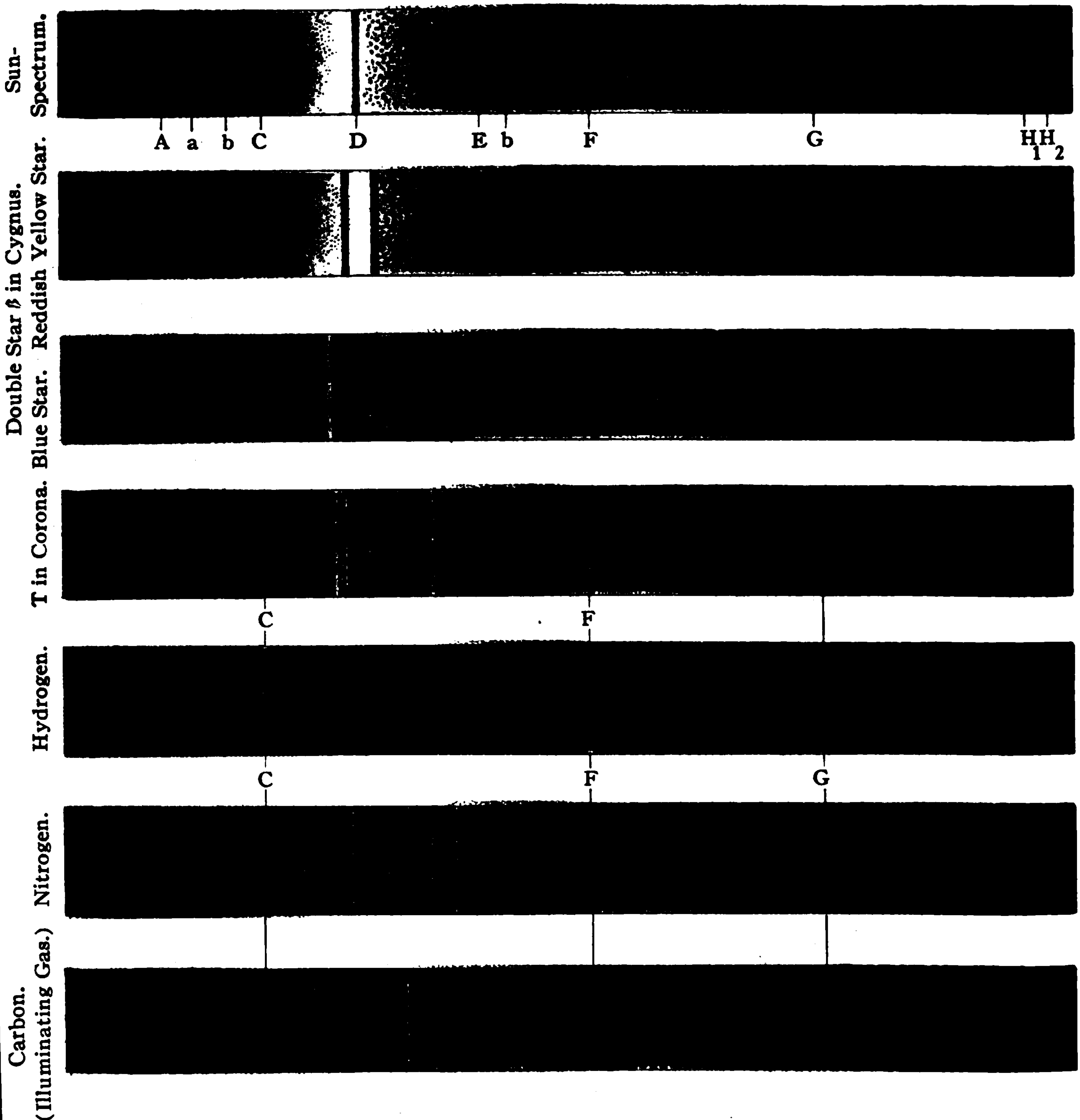
**367. Mixing Pigments.** When pigments are mixed, blue and yellow do not produce white as in mixing lights, but green. Each pigment absorbs certain colors. The yellow absorbs blue and violet and the blue absorbs red and yellow. Therefore green is the only color that is not absorbed by either the blue or the yellow. Always when pigments are mixed each one subtracts certain colors from white light; the resulting color depends upon the light waves that are not absorbed. The *primary pigments* are the complements of the three primary colors. They are, respectively, *peacock blue, crimson,* and *yellow.* When the three are mixed, all the colors are *subtracted* from white light and black is the result.

**368. Three-color Printing.** In three-color printing, three negatives of the same object are made through three color screens, each stained with one of the three primary colors. Halftone blocks are then made from these negatives in the usual manner. The colored plate is then printed on white paper, first with yellow ink, then with red, and finally with blue. The accuracy of the color reproduction depends upon the selection of inks of a shade exactly complementary to those shades used in making the color screens. See Frontispiece.

**369. Kinds of Spectra.** (1) *Continuous.* If we hold a platinum wire in the colorless flame of a Bunsen burner until it is white hot and then examine its spectrum, we find that it consists of an unbroken band of seven colors. The filament of an incandescent electric light produces the same result. A spectrum of this kind is said to be *continuous.* It has been found by experiment that *incandescent solids, liquids, or highly compressed gases yield continuous spectra.*

(2) *Discontinuous.* Let us dip a platinum wire into a solution of common salt and then hold it in a colorless flame. If we look through a narrow slit at the spectrum produced by the vapor burning above the wire, we find that it yields a bright yellow line. This bright yellow line is characteristic of the spectra of sodium compounds. The vapors of other metals yield bright-line spectra of different colors. When the spectrum produced by a platinum wire and that yielded by sodium vapor are both examined together, we find that the bright yellow line always appears in a certain position in the band of colors. When the wire is dipped into a solution of calcium chloride and than heated, we find that two bright lines appear, one in the green and the other in the red. *Luminous gases under ordinary pressure produce discontinuous or bright-line spectra.*

(3) *Absorptive.* Let us proceed to produce a bright-line spectrum of sodium vapor just as we did before. In an iron




SPECTRA OF THE FIXED STARS AND NEBULAE COMPARED WITH THE SUN-SPECTRUM AND OTHER SPECTRA

pan heat a little metallic sodium until it vaporizes and place it between the luminous vapor and the prism. Now when we look at the spectrum of sodium through an atmosphere of sodium vapor, we find that a *dark line* appears in the same position that the yellow line had occupied. The yellow light is absorbed by the sodium vapor. Such spectra are called *dark-line*, or *absorptive spectra. Gases or vapors absorb light waves of the same length they would produce if they were heated to luminosity.*

**370. Fraunhofer Lines.** The nucleus of the sun is surrounded by an atmosphere consisting of a large number of gases or vapors. Many substances which are solid on the earth's crust exist as vapor in the sun's atmosphere. The spectrum that the compressed nucleus of the sun would give if examined alone is continuous. The spectrum of its atmosphere would be discontinuous. Since vapors have the ability to absorb light of the same wave length they are able to yield when heated, the sun's spectrum shows a very large number of dark lines. Wollaston was the first to observe these lines in the sun's spectrum. They were independently discovered by Fraunhofer, who observed that they always appear in the same position as the bright lines produced by the luminous vapors of different elements. He charted about 600 lines which are found in the sun's spectrum; these dark lines are usually called *Fraunhofer lines.* Better methods of producing a long spectrum have since been discovered. In such a spectrum the number of lines is almost unlimited.

**371. The Spectroscope.** The spectroscope is an optical instrument used for examining spectra. It consists of a prism *P*, Fig. 354, mounted on a circular protractor. The collimator tube *C* receives light through the slit *S* and transmits it through the lens *L* so that the rays are parallel as they strike the prism. A small telescope *T* magnifies the spectrum which is produced by the prism. Cross-threads

in the telescope may be focused on any line in the spectrum and its angular position determined by means of the circular protractor.

**372. Spectrum Analysis.** In 1859 Bunsen was the first to use spectra for analytical purposes. This method of analysis furnishes very delicate tests for certain elements. Less than one millionth of a milligram of sodium can be detected by means of the spectroscope. Several elements have been discovered in the earth's crust by the use of the spectroscope. As early as 1868 helium was discovered in the sun's atmosphere by Lockyer. It was not discovered on the earth until 1895. Practically all of our astronomical knowledge of the composition of the sun and the other celestial bodies has been gained through the use of the spectroscope.

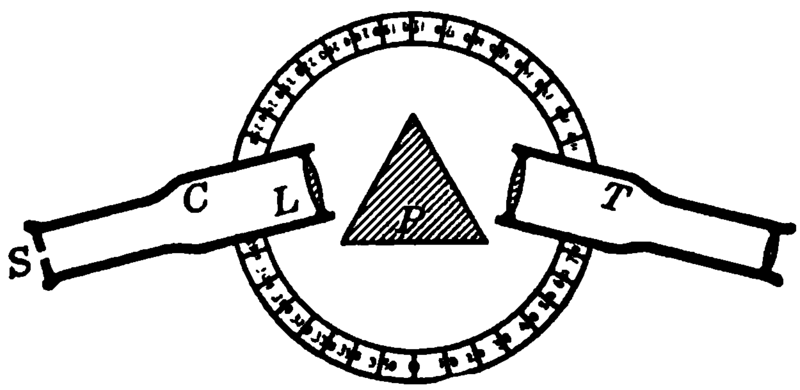


Fig. 354. — Spectroscope.

**373. Chromatic Aberration.** Light passing through the edge of a lens undergoes spherical aberration. In our experiment with the prism we learned that different colors have different indices of refraction; therefore light is also dispersed in passing through a lens. Since the violet light is bent more than the other colors, it is brought to a focus more quickly. See Fig. 355. A screen placed at $S$ shows an inner ring of violet surrounded by the other colors. If the screen is moved to the position $S'$, the inner ring will be red. Images formed by ordinary spherical lenses are always fringed with spectral colors. *The non-focus-*

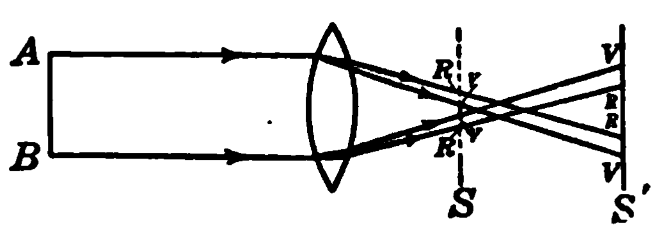


Fig. 355. — Chromatic aberration.

*ing of light of different colors is called chromatic aberration.*

**374. Achromatic Lenses.** In the latter part of the eighteenth century Dolland discovered that chromatic aberration may be remedied by using a combination of lenses consisting of crown glass and flint glass. See Fig. 356. The double convex lens is of crown glass; the plano-concave lens is made of flint glass. With such a system of lenses the dispersion is eliminated but not the refraction. *Achromatic lenses* produce an image without a fringe of colors. They are used in high-grade optical instruments.

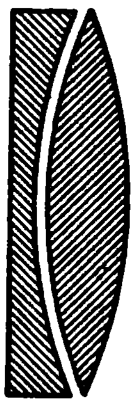


FIG. 356. — Achromatic lens.

**375. The Rainbow.** Light is dispersed by prisms, lenses, and also by drops of water. When the sun shines on drops of falling water, a solar spectrum called the rainbow may be cast across the sky. Fig. 357 shows the path a beam of sunlight takes in passing through a drop of water. As it enters the drop at $A$ it is refracted; dispersal also occurs. The red ray suffers total reflection at $R$ and the violet at $V$. When they leave the drop at $B$ both rays are again refracted. The angle these refracted rays make with the horizon of an observer as he stands with his back to the sun is 40° for the violet, and 42° for the red rays. In the actual bow which the observer sees the red rays come from drops of water at an angle of 42°, and the violet from those at an angle of 40°. The other colors are formed by drops between these angles. The rainbow is an arc, since the eye of the observer is at the tip of a cone from which he sees the colored rays refracted from drops in all directions at angles of from 40° to 42°.

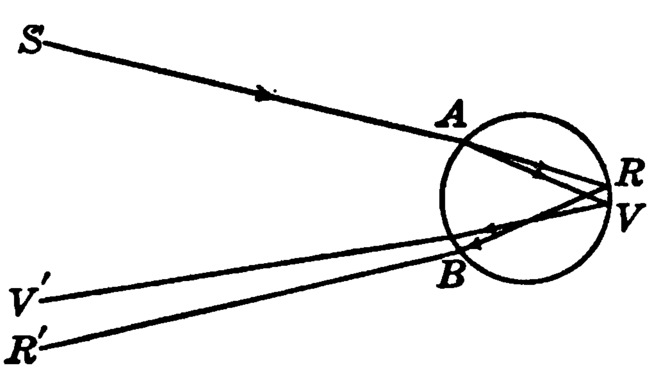



FIG. 357. — Rainbow produced by refraction, total reflection, and dispersion.

Sometimes a larger *secondary* bow is seen above the *primary*. The colors are here reversed, the violet being on the outside. The light is refracted from drops of water at an angle of from 51° to 54°. It enters the lower part of the drop, is refracted and dispersed as in the primary bow, but it is *twice totally reflected* before it leaves the drop. For this reason more light is absorbed, and the secondary bow is always fainter than the primary bow.

**376. Interference.** Just as one sound wave may be superimposed upon another to strengthen or diminish sound, so light waves may interfere with one another. A wedge-shaped film of air between two pieces of glass, one plane and the other slightly convex, may be used to illustrate this phenomenon. Both pieces of glass reflect a part of the light. It is possible to have the air film of such thickness that the two reflected rays meet either in opposite phases or in the same phase. If a sodium flame, which gives yellow light only, is used, the rays meeting in opposite phase will interfere and produce a dark band; those that meet in the same phase will intensify the light, producing a bright yellow band. When sunlight is used, bands of spectral colors are produced, since the air film is wedge-shaped and the wave lengths corresponding to different colors interfere at different positions. The air film between oil and water, or in a cracked piece of ice or glass, shows spectral colors when it is viewed from an oblique angle. The light waves reflected from the two surfaces which are separated by the air film meet in opposite phases, thus producing spectral colors by interference.

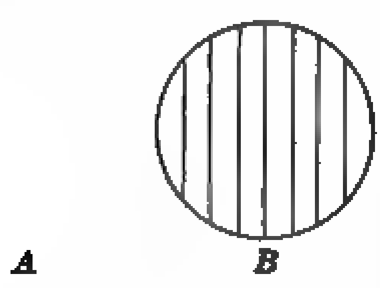



FIG. 358. — *A*. Possible appearance of end of beam of light. *B*. of polarized light.

**377. Diffraction.** When the wave theory of light was proposed, its opponents argued that light waves should not

cast shadows, but should bend around corners as sound waves do. Experiment shows that very short sound waves do cast shadows to some extent, and that light waves under certain circumstances do bend out of their course slightly. When light is transmitted through an opening that is small in comparison with its wave length, the wave spreads out and produces spectral colors by interference. This phenomenon, which is known as *diffraction*, may also be produced by reflection of light from an opaque surface that is striated.

By means of a diamond point 15,000 to 30,000 lines to the inch have been ruled on glass, or on speculum metal. Such a ruled plate is called a *diffraction grating*. With a glass grating light is transmitted through the narrow space

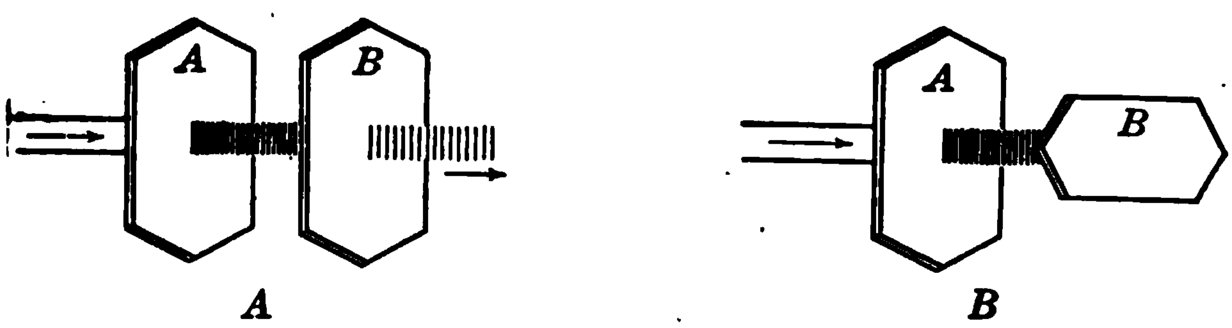



FIG. 359. — Effect of tourmaline crystals.

between the lines and spreads out, or is diffracted. Such a grating is much better than a prism for examining spectra, since the colors do not overlap and the spectrum that is produced may be several feet in length. The plumage of some birds, and some changeable silks have a beautiful play of colors on account of diffraction.

**378. Polarization.** Sound waves are longitudinal; light waves are transverse vibrations of the ether in all directions. Fig. 358 $A$ may be used to represent a cross-section of a beam of light with a few of the directions of vibration included. If all the vibrations are in one plane, as in Fig. 358 $B$, we call it a *plane of polarized light.* Certain crystals, tourmaline, for example, have the property of transmitting *only* those light waves whose plane lies in the same direction as the axis of the crystal. Fig. 359 $A$ represents two tourmaline crystals

with their axes parallel. A complex beam of light enters the first crystal at *A* and is polarized, passing through both crystals in the plane of their axes. In Fig. 359 *B*, the beam is polarized by *A* in exactly the same manner. The axis of *B*, however, is turned perpendicular to the plane of light; therefore no light is transmitted. The tourmaline tongs of Fig. 360 illustrate polarization. Either crystal used alone transmits light, but when their axes are at right angles, all light is intercepted. The vibrating rope shown in Fig. 361 also serves as an illustration.

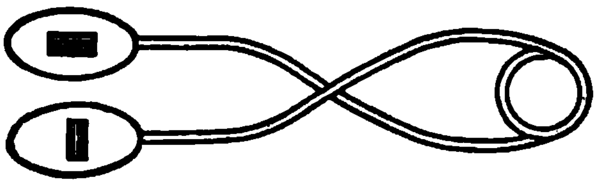


FIG. 360. — Tourmaline tongs.

The *polariscope* is constructed on the same principle. One crystal polarizes the light; it is called the *polarizer*. The other crystal, which is called the *analyzer*, may be readily rotated. Some substances have the ability to twist or turn the plane of polarized light. Glucose, sugar, and many organic substances have this property. Suppose we have the two crystals of a polariscope turned as in Fig. 359 *B* so that no light passes, and a sugar solution is then placed between them. The sugar solution turns the plane of polarized light to such an extent that it will again pass through the analyzer. The analyzer must now be rotated a certain number of degrees in order to intercept this twisted plane. The amount of rotation required depends upon the kind of substance used and upon the strength of the solution. Substances that turn the plane to the right are called *dextro-rotatory*. Dextrose is an example. Substances that twist the plane to the left are called *levo-rotatory*. Levulose is an example. The polariscope is used to test the strength and purity of substances, especially of sugars.

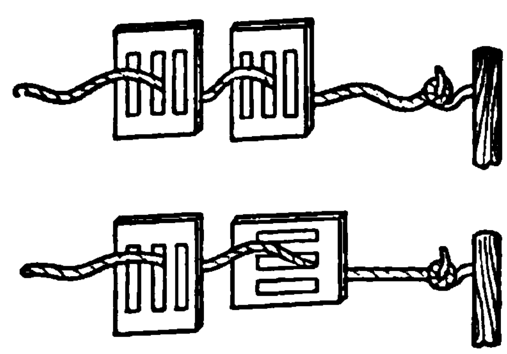


FIG. 361. — Rope vibrations to represent polarization.

## SUMMARY

Since light waves of different color have different refrangibility, light is scattered or dispersed by refracting media. Dispersal from raindrops produces the rainbow. The dispersion of light by lenses which produce a color-fringed image may be remedied by the use of achromatic lenses.

Color is analogous to pitch; it depends upon the length of the light waves, or upon the frequency of vibration. The color of an opaque object depends upon the color of the light it receives and upon the color of the light it can reflect. Any two colors that combine to produce white light are complementary.

Incandescent solids, liquids, and compressed gases yield continuous spectra; luminous gases produce bright-line spectra. Gases absorb light waves of the same length they would emit if heated to luminosity.

## QUESTIONS

1. What do we mean when we say an object is red?

2. The Cooper-Hewitt mercury vapor lamp is deficient in red rays. What effect does its light have upon the appearance of persons in a room where it is used?

3. Doppler's principle applies to light waves. A luminous body moving toward the earth has its light waves shortened. Would the lines of its spectrum be displaced toward the violet end of the spectrum or toward the red?

4. Do two persons see the same rainbow? Explain.

5. Why is the rainbow curved? Can the complete circle ever be seen?

6. Do you think it is possible to have a rainbow at noon in July? Is a rainbow at noon possible in January? How would the latitude of a place affect your answer?

7. Does iron which is heated white hot give off red rays of light? How could you prove your answer?

8. If black objects absorb all the light they receive, how is it that we see them?

9. What color do objects appear when viewed through a piece of red glass?

# CHAPTER 21

# MAGNETISM

## *A.* NATURE OF MAGNETISM

**379. Natural Magnets.** Certain kinds of iron ore found in several localities have the property of attracting pieces of iron or steel. Bodies that have this property are called *magnets*. The name is probably derived from the fact that the iron ore *magnetite* is found in Magnesia, Asia Minor. When pieces of this ore are so suspended that they are free to take any position, they always assume a north-and-south line. For this reason they are called *lodestones* (leading stone). As early as the twelfth century lodestones began to be used in Europe to indicate directions.

**380. Artificial Magnets.** Although natural magnets are widely distributed, yet the magnets which are in common use are artificial. It is possible to make an artificial magnet by stroking a bar of steel with a natural magnet, always beginning at the same end. The natural magnet must be returned to the starting point each time through the air-gap. Later the student will learn how to make a magnet by passing an electric current through a wire wound around a bar of steel or iron.

**381. Magnetic and Non-magnetic Materials.** We have learned that iron and steel are *magnetic* materials. Cobalt and nickel are also attracted by a magnet, though to a lesser degree. Certain alloys have been made that are magnetic, but for practical work iron or steel is used when

magnetic material is needed. Most substances are *non-magnetic.* They are not affected in any way by the magnet. A few substances, antimony, bismuth, zinc, and tin, are actually repelled by the magnet, although the effect is small. They are *diamagnetic.*

**382. Polarity.** When a magnet is dipped into iron filings and then lifted, it is found that the filings cling to the magnet at or near the ends only. See Fig. 362. The magnetic force of attraction appears to be concentrated near the ends of the magnet. These points at which the magnetism appears to be concentrated are called *poles.* That pole of a freely swinging magnet which points to the north is called the north-seeking pole; it is often called merely the north pole, the N-pole, or the + pole. The other pole of the magnet is the south-seeking pole; it is also called the south pole, the S-pole, or the − pole.

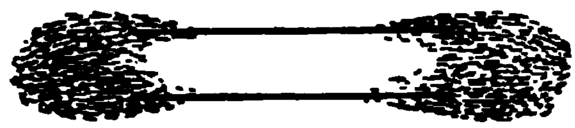


FIG. 362. — Polarity.

**383. Laws of Magnets.** When the N-pole of a magnet is brought near the N-pole of another magnet, suspended as in Fig. 363, repulsion occurs; if the two S-poles are brought near one another, they also repel. If we hold the N-pole near the S-pole of the suspended magnet, the two poles attract. These experiments verify the law of polarity: *Like poles repel; unlike poles attract.* The force of attraction is directly proportional to the product of the strengths of the poles and inversely proportional to the square of the distance between them. (Compare with the law of gravitation.) A pole is said to be of unit strength when it repels an exactly similar pole one centimeter distant with a force of one dyne.

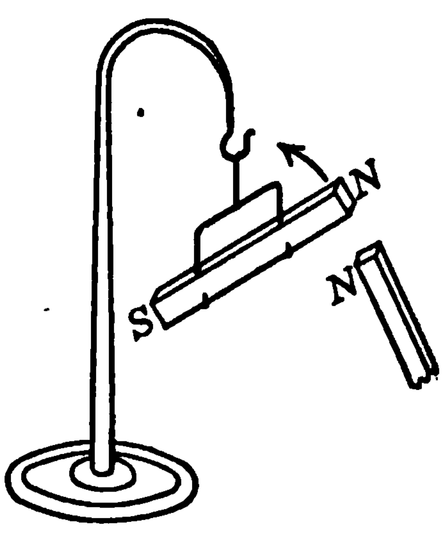



FIG. 363. — Like poles repel.

**384. Magnetic Needle.** The compass, Fig. 364, consists of a small bar magnet balanced on a pivot, or so suspended that it is free to assume any direction. The use of such a magnetized needle to indicate directions made navigation much safer than it had been before. It made possible the series of explorations that eventually led in the fifteenth century to the discovery of America. The magnetized needle is also used in several electrical instruments.

Fig. 364. — Compass.

**385. Retentivity.** When a piece of *soft* iron is stroked with a magnet, it is *easily* magnetized. In a short time, the soft iron loses nearly all its magnetism. Such a magnet is a *temporary* magnet. Soft iron is used when we wish to have a substance magnetized quickly and demagnetized quickly. A small amount of the magnetism is usually retained; it is known as *residual* magnetism. Silicon steel is an alloy that has little retentivity; it is used in making the cores of electro-magnets.

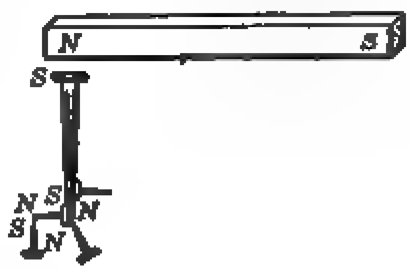


Fig. 365. — Magnetic induction.

It is much more difficult to magnetize a bar of steel, but it retains its magnetism a long time. Steel is used for making the so-called *permanent* magnets. We say steel has high *retentivity* because it is hard to magnetize and hard to demagnetize. Tungsten steel is especially difficult to magnetize and its retentivity is very high.

**386. Magnetic Induction.** If we hold a bar magnet *near* or *in contact with* a soft iron nail as in Fig. 365, the nail becomes a magnet by *induction.* As long as the bar magnet is held near the nail it retains its magnetism, and several tacks may be picked up; if the bar magnet is removed, the tacks fall off. *Magnetism produced in this manner by the presence of a magnet is called induced magnetism.* A small compass needle may be used to show that the nail became a magnet with its S-pole adjacent to the N-pole of the magnet; the remote end is its N-pole. Any piece of iron may be temporarily magnetized in this manner by being brought near a magnet.

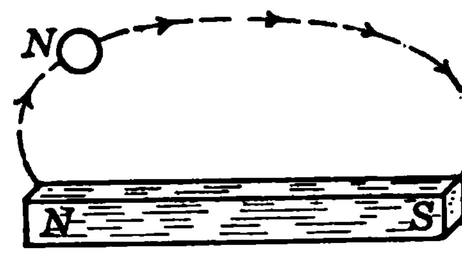


FIG. 366. — Line of force.

**387. Lines of Force.** *The path that an independent N-pole would take in going from the north-seeking pole of a magnet to its south-seeking pole is called a line of force.* Since the north-seeking pole is repelling and the south-seeking pole is attracting this N-pole, in each case with a force inversely proportional to the square of the distance, its path will be a curve similar to that shown in Fig. 366.

It is not possible to get an independent N-pole, but by using a Mayer's floating magnet consisting of a magnetized needle thrust through a cork so it will float vertically, as in Fig. 367, the result is essentially the same. If we place a bar magnet under the trough, the path taken by the floating magnet is practically the curve shown in Fig. 366.

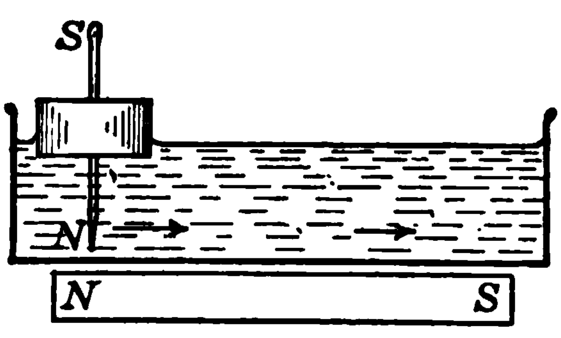


FIG. 367. — Path of floating magnetic pole.

Magnetic lines of force are believed to form closed curves, continuous from the N-pole through the air-gap to the S-pole, and through the magnet to the N-pole. They act like elastic bands stretched from pole to pole of the magnet.

Lines of force repel each other. If a compass is placed in a magnetic field, its needle always takes a position parallel to the lines of force. The lines of force are most numerous at the poles, where magnetic force appears to be concentrated.

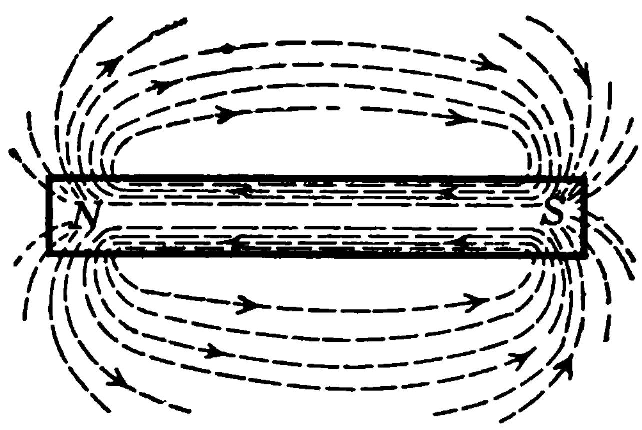



Fig. 368. — Lines of force. Single magnet.

**388. Magnetic Field.** Any space permeated by lines of force is a magnetic field. A field of unit strength has one line of force, or *maxwell*, per square centimeter. The area is always considered perpendicular to the line of force. A magnetic field of unit intensity is called a *gauss*.

A permanent chart of a magnetic field may be easily made by pinning a blue-print paper over a magnet which rests in a grooved board, and sifting iron filings over it. When the board is tapped gently the filings arrange themselves in the direction of the lines of force. After exposure to the light for a few minutes, the print is developed in the usual manner. Fig. 368 shows the field of force about a single bar magnet. If two magnets are used with poles adjacent, the flexibility of the lines of force is clearly indicated.

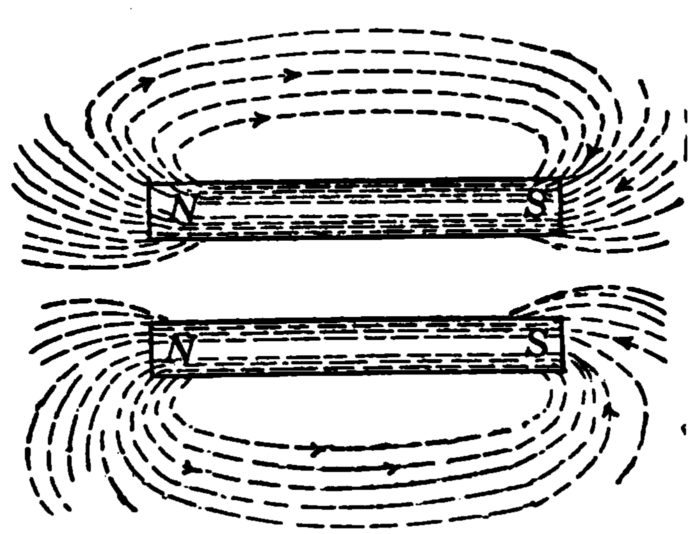



Fig. 369. — Lines of force. Like poles adjacent.

**389. Magnetic Transparency and Permeability.** In § 388 we learned that a magnet exerts its influence on iron filings through blue-print paper. When sheets of various metals, such as copper, tin, lead, zinc, or aluminum, are used in a similar manner, we find that nearly all of them are *transparent* to magnetism. The lines of force cut across the non-magnetic materials without being absorbed.

If we repeat the experiment, using a sheet of iron, the result is not the same. The lines of force do not pass *across* the iron; they enter the iron readily and follow a path within

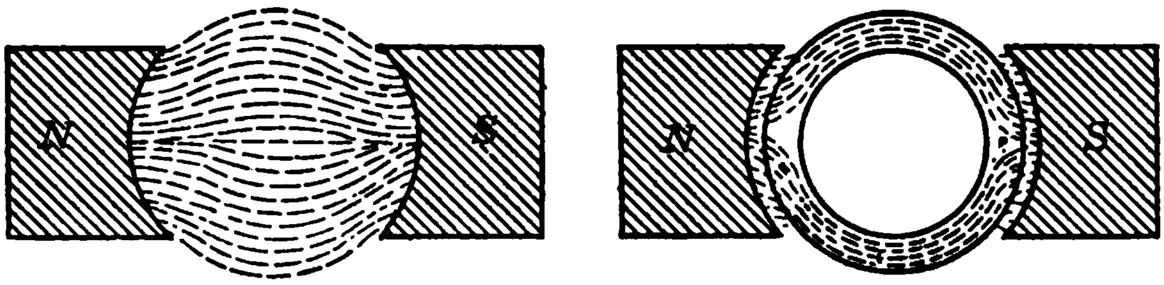
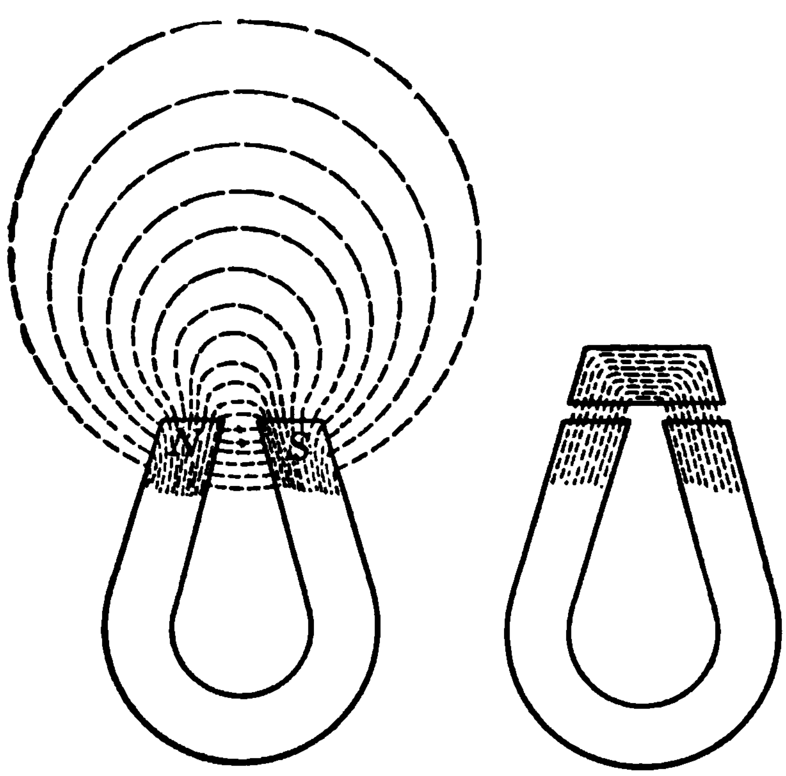


FIG. 370. — Permeability of soft iron. Note effect of ring on lines of force.

the iron itself. Fig. 370 shows the lines of force passing across the air-gap between the two poles of a horseshoe-shaped magnet. In the same figure, we see the effect of introducing an iron ring between the two poles. The lines of force prefer the iron to any other medium. We say that iron is very *permeable*, since it readily *gathers in* lines of force and affords an excellent path for their transmission.



*A* *B*

FIG. 371. — *A*. Horseshoe magnet. *B*. Effect of armature.

**390. The Shape of a Magnet.** From a study of the examples of permeability, we can understand why magnets are usually made in the shape of a horseshoe, rather than that of a straight bar. Suppose we bend a bar magnet until the two ends are quite close together. The air-gap between the two poles has been very much decreased. The intensity of the field is much greater, due to the concentration of the lines of force. Compare the concentration of the lines

of force about a bar magnet, Fig. 368, with that of a horseshoe magnet, with and without the iron armature, Fig. 371 *A* and *B*. The latter figure also shows the high permeability of iron.

**391. Theory of Magnetism.** If we break a bar magnet, we do not destroy its magnetism. Four poles are formed, as in Fig. 372. We may continue to break it, but each small piece still has polarity. This leads to the theory that the molecules themselves are small magnets and have polarity. If a magnetized knitting needle is heated in the middle and then twisted sharply, additional poles are produced; they are called *consequent* poles. Such poles are sometimes found in bar magnets. In an unmagnetized bar the molecules are probably arranged as in Fig. 373 *A*, so heterogeneous that they mutually neutralize one another. As we move a magnet along such an unmagnetized bar, a part of the molecules would tend to arrange themselves as in Fig. 373 *B*. The bar is then *partially* magnetized. When a bar of steel is *saturated* with magnetism, according to this theory, the molecules occupy positions as shown by Fig. 373 *C*. The fact that a glass tube filled with iron filings may be magnetized by stroking it with a magnet is evidence of the correctness of the theory. The magnetism disappears when the tube is shaken vigorously. Each filing is probably an independent magnet, but if they are arranged with like poles adjacent, one neutralizes the effect of the other.

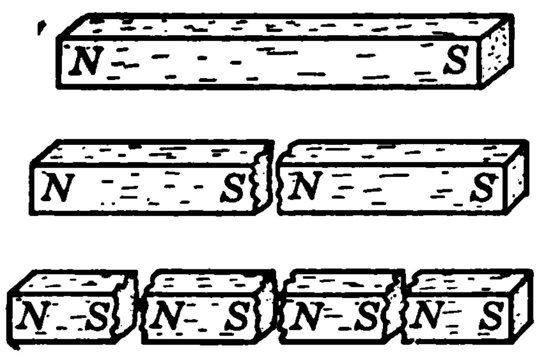



FIG. 372. — Effect of breaking a magnet.

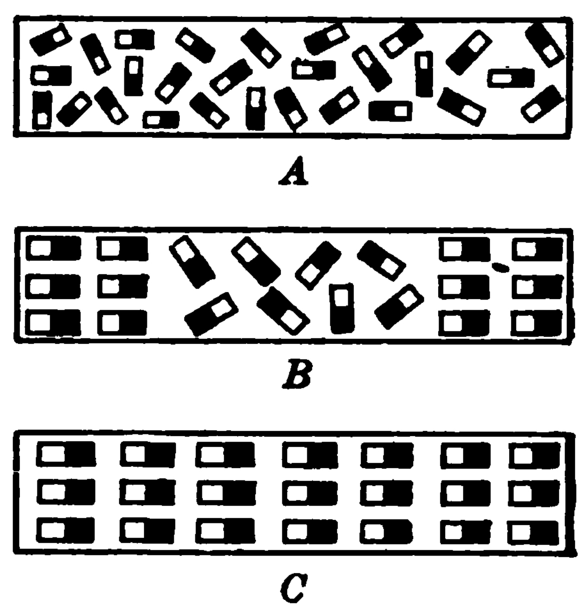



FIG. 373. — *A*. Unmagnetized bar. *B*. Partially magnetized. *C*. Saturated bar.

Pounding a magnet or dropping it causes it to lose some of its magnetism. Heating it to a red heat destroys the magnetism; the high temperature increases the ease with which the molecules oscillate. The more mobile the molecules, the easier the substance will be magnetized, but the molecular condition will also be more easily disturbed. Soft iron is easily magnetized, but it loses its magnetism readily. The difficulty with which steel is magnetized and its high retentivity are probably accounted for by the greater immobility of its molecules.

## *B.* TERRESTRIAL MAGNETISM

**392. The Earth a Magnet.** The earth in its effect upon magnetized objects and magnetic materials acts as if it were a huge magnet. Its lines of force appear to be concentrated at the earth's magnetic poles. The magnetic pole of the northern hemisphere has been discovered at about 70° North Latitude and 96° West Longitude. We may think of this pole in two ways. If we consider it the earth's North Magnetic Pole, then the north-seeking pole of a compass needle must be a south pole, since unlike poles attract. Otherwise we must think of the magnetic pole in the northern hemisphere as the earth's south pole and the north-seeking pole of the magnetic needle as a true north pole. The latter is less logical, but the term north pole as applied to the north-seeking pole of a magnetic needle is much more commonly used. It matters little how one thinks of it, provided the student remembers that the term north pole, N-pole, or + pole refers to that end of a compass needle which seeks the north. The South Magnetic Pole of the earth has been discovered at about 72° South Latitude and 155° East Longitude. The earth's lines of force may be considered *magnetic meridians* extending from one magnetic pole to the other magnetic pole.

**393. Magnetic Declination.** If the earth's North Magnetic Pole and its North Geographic Pole were coincident, the north-seeking pole of a compass needle would everywhere point to the true north. Since the magnetic pole is about 20° south of the geographic pole, the compass may point to the North Magnetic Pole without pointing to the true north, or to the North Geographic Pole. Columbus was

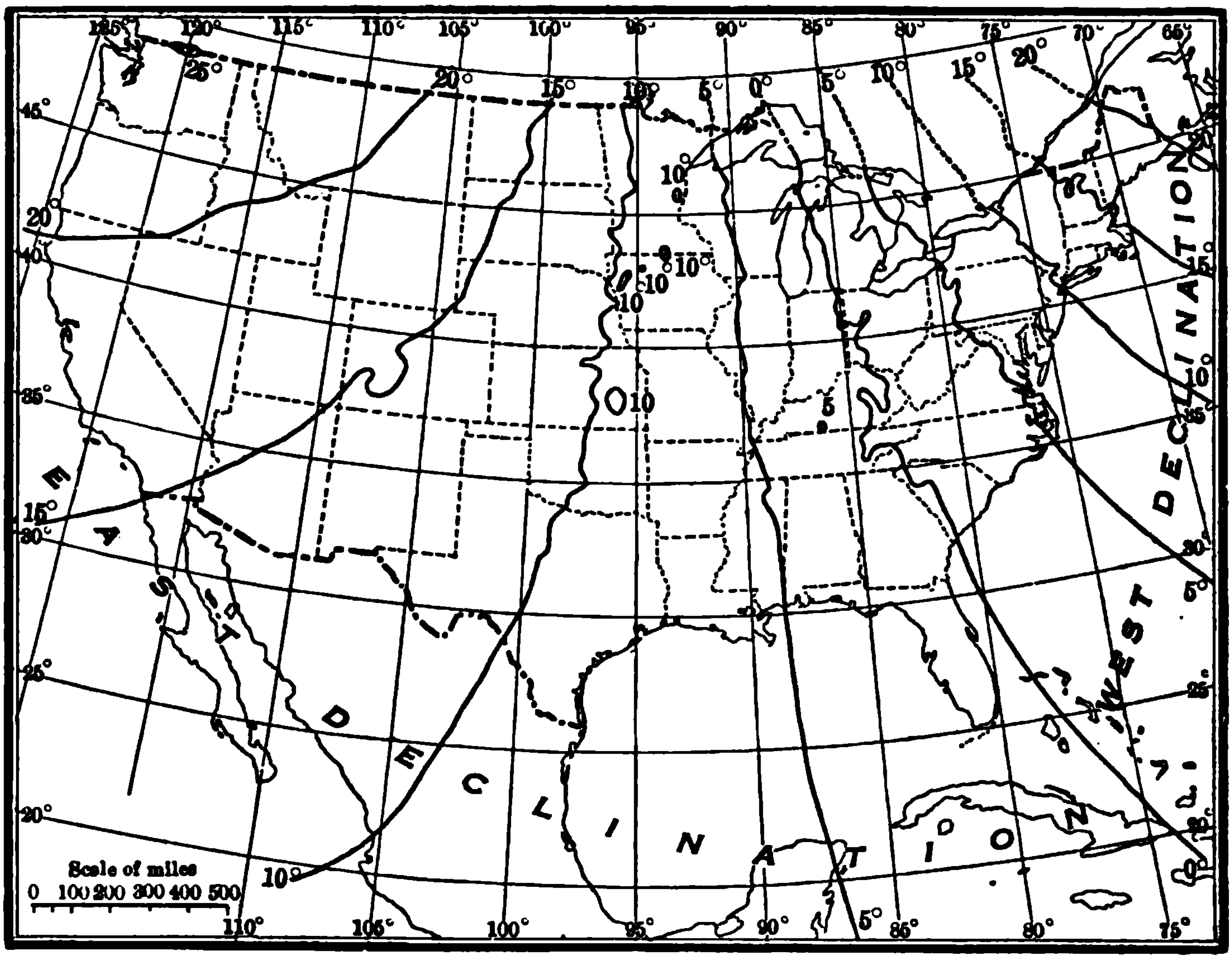



FIG. 374. — Chart of isogonic lines. (*Courtesy of U. S. Coast and Geodetic Survey*)

the first to notice the variation of the compass needle in different localities. His sailors were so thoroughly alarmed by these variations of the needle that they threatened to mutiny and throw Columbus overboard. The angle between the true north, and the north as indicated by the compass needle, is called the *angle of declination; it is the angle of deviation of the magnetic needle from the true north.* Lines drawn through places on the earth's surface having the same

declination are called *isogonic* lines. See Fig. 374. Lines drawn through places having no declination are called *agonic* lines. A line of zero declination passes through South Carolina, eastern Tennessee and Kentucky, Western Ohio, and Michigan. For places East of this line, the declination is West; for places West of the line, it is East.

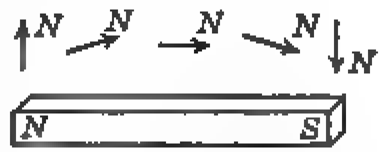


FIG. 375. — Magnetic dip.

The angle of declination varies slightly from year to year. In 1831 when the earth's North Magnetic Pole was found by Sir James Ross, it was located at 70° and 30′ N. Latitude, and 95° W. Longitude. In the year 1905 it was again located by Captain Amundsen almost 2 degrees farther West. Its position at that time was about 70° and 5′ N. Latitude, and 96° and 46′ W. Longitude. This slow westward migration of the magnetic pole causes the variation in the declination. Before a surveyor begins

FIG. 376. — Dipping needle

ed tract of land, he establishes a
neasures the declination.

ion or Dip. If we place a small
and slide it along from one end
manner shown in the diagram of

Fig. 375. Near the middle it is horizontal. It dips when placed at either end of the magnet.

A compass needle mounted on a horizontal axis so that its dip may be measured is called a *dipping needle*. Fig. 376. At places on the earth's surface midway between the magnetic poles the dip is zero. A line drawn through places on the earth's surface where the dip of the needle is zero is called the *magnetic equator*. It is an *aclinic* line. Lines drawn through places having the same *dip* or *inclination* are called *isoclinic* lines. At the magnetic poles the needle stands at an angle of 90°, or in a vertical position.

**395. Inductive Action of the Earth.** Pieces of iron which have been lying in contact with the earth for some time usually show some signs of polarity. This is especially apt to be true if they lie parallel to the earth's magnetic meridian. Since the earth acts as if it were a huge magnet, magnetic materials in contact with it are *magnetized by induction*. Let us hold an iron rod in the direction of the earth's meridian with the north end slanting down at an angle of about 70°. If we strike the rod a few blows with a hammer, it will when tested be found to have polarity. Now let us reverse the rod and strike it as before. When it is again tested for magnetism, the polarity is found to have been reversed. The rod may be demagnetized by holding it at right angles to the magnetic meridian (East and West) and striking it a few blows with a hammer.

## SUMMARY

A magnet may be made by stroking a bar of steel with a lodestone, always beginning at the same end. Its magnetism may be destroyed by heating it, or by pounding it, if it is held at right angles to the magnetic meridian.

The magnetic force appears to be concentrated at or near the ends of the magnets at points called poles. The north-seeking pole of a freely swinging magnet seeks the North Magnetic Pole.

Like poles repel; unlike poles attract. A single line of force is called a maxwell. A line of force perpendicular to an area of one square centimeter gives a magnetic field of unit strength; it is called a gauss.

The earth is a huge magnet. It acts inductively upon magnetic materials near or in contact with it, magnetizing them.

The compass needle does not point to the true north at all places. The angle of deviation of the magnetic needle from the true north is called the magnetic declination.

## QUESTIONS

1. When bar magnets are held together with unlike poles adjacent, they show little attraction for magnetic materials. When held with like poles adjacent, the attraction is increased. Explain.

2. Iron posts and pillars are usually slightly polarized. Explain. Is the top an N-pole or an S-pole?

3. Why is polarity the best test for magnetism? Why is repulsion a surer test for magnetism than attraction?

4. If an iron bar attracts either end of a compass needle, is it magnetized? Give a reason for your answer.

5. If the balance wheel of a watch becomes magnetized, the watch fails to keep good time. How may the works of a watch be protected against magnetization?

6. Could Peary have reached the North Pole by following the direction indicated by the north-seeking pole of a compass? Explain. In what direction would the north-seeking pole of a compass point from the North Geographic Pole?

7. In an unsurveyed territory, how could you find the true north? How could you find the magnetic declination?

8. How can a dipping needle be used to indicate the presence of beds of magnetic iron ore?

9. How would you expect the declination of the compass to be affected by the presence of large beds of magnetite?

10. Why is the gyro-compass now used on submarines and many battleships?

11. When not in use, two bar magnets should be packed in a box with unlike ends adjacent, and two strips of soft iron joining the poles. Why?

## CHAPTER 22

# ELECTRICITY — STATIC OR FRICTIONAL

**396. Historical.** As early as 600 B.C., Thales, a Greek philosopher, is said to have discovered that a piece of amber which has been rubbed with flannel attracts small pieces of paper or pith. It seems to have been about 2200 years before any one discovered that many other substances have the same property. Gilbert, an Englishman, who made this discovery about 1600 A.D., gave the name *electricity* to the phenomena produced in this manner.

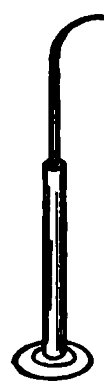


FIG. 377. — Pith-ball electroscope.

**397. Electricity Produced by Friction.** Every student has noticed the crackling sound produced by stroking a cat's back in dry cold weather. No doubt he has also produced an electric spark by shuffling his feet over a rug or carpet and then touching a radiator or some other metallic object. When a glass rod is rubbed with silk, it is also electrified. To show that the glass rod carries an electric charge, we may hold it near a pith-ball suspended by a silk thread. The pith-ball is first attracted and then repelled. The same effect is produced if we rub a piece of sealing wax with flannel, or a rod of vulcanite with catskin. See Fig. 377. It is interesting to note that the silk, flannel, and catskin, also show electrification when tested in the same manner.

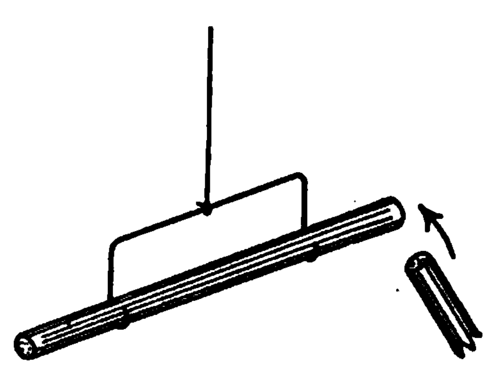


FIG. 378. — Repulsion between like charges.

**398. Electricity Is of Two Kinds.** Let us suspend an electrically charged glass rod as shown in Fig. 378, and bring near it a similarly charged rod. The rod is repelled. If we bring near the suspended rod a piece of vulcanite that has been rubbed with fur, the two rods attract. From this experiment it is obvious that there are *two kinds of electrification.* The one produced on glass by rubbing it with silk is called *positive,* or *plus electricity;* the other produced on vulcanite by rubbing it with fur is called *negative,* or *minus* electricity. This experiment also teaches us that *like electrical charges repel* and *unlike electrical charges attract.*

**399. The Electroscope.** The pith-ball which we used to detect the presence of an electrical charge was first attracted by the glass rod; while they were in contact the charge from the rod spread over the pith-ball until it became charged with electricity of the same sign. Then repulsion occurred. The pith-ball electroscope is not nearly so sensitive as the instrument shown in Fig. 379. A brass rod terminating in a ball or disc $A$ is thrust through a rubber stopper. To the end $B$ two strips of gold leaf or aluminum foil are attached, and the whole is then placed in a glass flask. An electrical charge applied to the ball or disc spreads to the leaves; since both leaves are thus charged with electricity of the same sign, they repel one another.

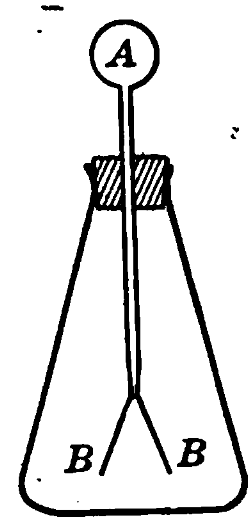


FIG. 379.—Simple gold leaf electroscope.

To avoid tearing the leaves by too intense a charge, a *proof-plane* is often used. It consists of a metal disc cemented to a rod of glass or vulcanite. In use the disc is applied to the charged object and then touched to the knob of the electroscope. A very efficient electroscope now used extensively in work with radio-active substances is shown in Fig. 380. Such *an instrument may be used to detect the presence*

***of an electric charge, to determine its sign, or to measure its intensity.***

**400. Conductors and Insulators.** Let us support a brass ball by a silk thread and then connect it with an electroscope by means of a copper wire. See Fig. 381. When the ball $B$ is charged electrically, the charge is transmitted along the copper wire to the electroscope, whose leaves diverge. Now let us replace the copper wire with a silk thread. A second charge applied to the ball is not transmitted to the electroscope, and there is no divergence of its leaves. Materials which readily transmit an electric charge are called *conductors.* The metals are good conductors; especially silver, copper, aluminum, and iron. Materials which do not readily conduct an electric charge are called *insulators.* Glass, porcelain, shellac, resins, oils, silk, wool, sulphur, *dry* air, rubber, gutta-percha, bakelite, mica, and paraffin are among the best insulators. Since all substances offer some resistance to the passage of electricity through them, there are no perfect conductors. On the other hand, no insulator is perfect; hence the term "conductance" is a relative one. Cotton, dry wood, impure water, and acids, bases, or salts in solution are sometimes called *semi-conductors.* Pure water is an insulator.

FIG. 380. — An electroscope.

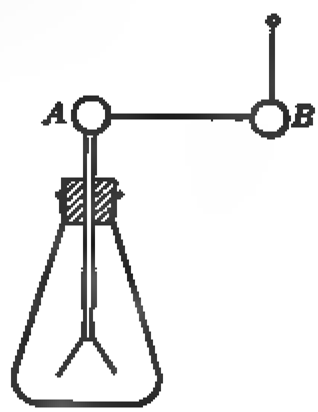



FIG. 381. — Conduction of electricity.

**401. Theory of Electricity.** No one is able to say just what electricity really is. We know electricity best from a study of the effects which it produces. Several theories

**Benjamin Franklin** (1706-1790) was an American scientist and inventor. Every school boy knows the story of the kite which Franklin flew in a thunderstorm. By means of this device he proved that lightning and electricity are identical. Franklin is the author of the "one-fluid" theory of electricity. He invented the lightning rod and the Franklin stove which replaced the old-fashioned fire-place.

**Hans Christian Oersted** (1777-1851) was a Danish physicist. In 1819 he made his discovery showing the connection between electricity and magnetism. He showed that a current flowing through a conductor sets up a magnetic field around the conductor. A magnetic needle brought into this field is deflected. This experiment paved the way to the discovery of the electro-magnet and the galvanometer.

have been advanced, however, in an effort to explain the nature of electricity. The *electron* theory is the most modern and in many ways it seems the most plausible. This theory assumes that the atoms of matter consist of both positive and negative electricity. Each atom consists of a positive nucleus surrounded by very minute negative particles called *electrons*. It is believed that the electrons are very much smaller than the positive nucleus, and that they revolve around it at very great speed. In the normal atom, the sum of the negative charges just equals the charge of the positive nucleus. Such an atom is neutral; it shows no sign of electrification. When a glass rod is rubbed with silk, some of the electrons leave the glass and are transferred to the silk. Since the glass is then deficient in electrons, it is positively charged; the excess of electrons imparts to the silk a negative charge. If we wrap the glass rod in the silk and hold both of them near an electroscope, there is no sign of electrification. When they are separated again, either one will cause the leaves of an electroscope to diverge. A current of electricity flowing through a conductor is a stream of electrons. The mass and speed of electrons have been determined, and their behavior in a magnetic field is well known.

Although the electron theory is so well established, the conception of electricity as a fluid has prevailed for so long a time that the names and signs used by Benjamin Franklin are still in use. According to Franklin's theory, electricity is a *fluid*. An object which is positively charged has an excess of the electrical fluid; if an object has less of the electrical fluid than normal, it is negatively charged. Just as heat is believed to flow from an object at a high temperature to one of lower temperature, so it was considered by Franklin that electricity flows from the positive (plus) to the negative (minus). In all diagrams it is still assumed that electricity flows from plus (+) to minus (−), although we are quite certain that the reverse is true.

**402. Electrification by Induction.** We have seen that an object may be electrified by *contact and conduction.* When an electrically charged object is brought *in contact with* a conductor, the charge spreads over the conductor until both are charged throughout with electricity of the same sign. If the charged object is brought *near* a conductor, the conductor is charged by *induction.* In Fig. 382, the rod $C$ carries a positive charge; it acts by induction through the air-gap which is an insulator. According to the electron theory, an excess of electrons will be attracted to $A$, the *near* end of the conductor; the more *remote* end of the conductor is deficient in electrons, and its sign is positive. In such cases, *electricity of opposite sign is always induced in the end of the conductor near the charged object; electricity of the same sign is induced in the more remote end of the conductor.* Induction acts through or across all insulators.

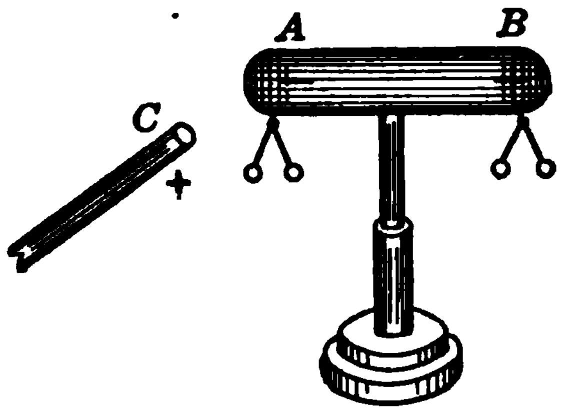


FIG. 382. — Electrostatic induction.

**403. Charging an Electroscope by Induction.** Let us bring a negatively charged rod near the knob of an electroscope as in Fig. 383 *a.* The electrons are repelled and stream away from the knob to the leaves, thus charging them negatively by induction. The deficiency of electrons on the knob leaves it charged positively. If the rod is removed, the electrons will again distribute themselves uniformly over the knob and leaves, and there will be no evidence of electrification. Suppose, however, that we touch the knob

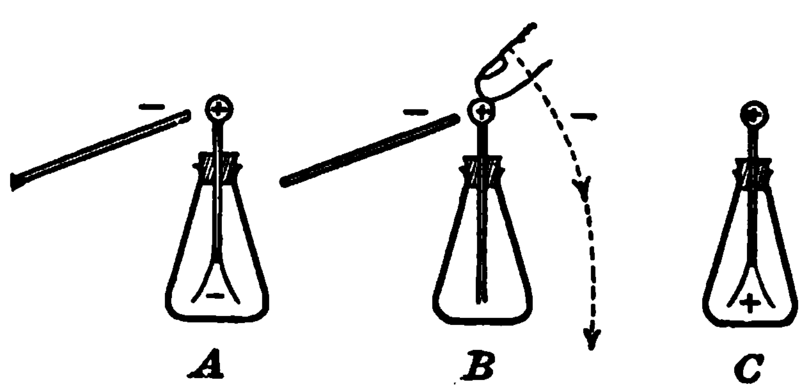


FIG. 383. — Charging electroscope by induction.

with a finger while the rod is still held near the knob, as in Fig. 383 *b*. In this case the electrons are repelled to the earth through the human body, which is a fair conductor. It is customary to think of the positive electricity as being "bound" by the rod; therefore it does not escape. We have thus separated the electrons from their positive nuclei, producing thus essentially the same effect as the removal of electrons from a glass rod when it was rubbed with silk. Next we may remove the finger and subsequently the rod. The leaves do not collapse, because the electroscope is now positively charged by induction. See Fig. 383 *c*. By using a glass rod which has been rubbed with silk, an electroscope may be charged negatively.

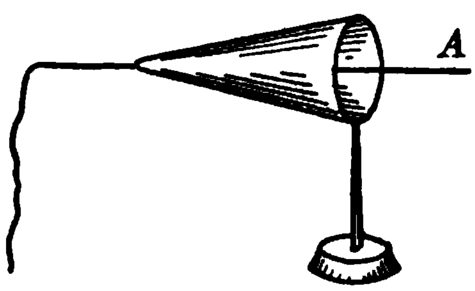



FIG. 384. — Faraday's experiment.

A charged electroscope may be used to determine the sign of an electric charge. For example, a proof-plane is touched to the object of unknown sign and then brought in contact with the knob of a *positively* charged electroscope. If the sign of the unknown body is positive, the divergence of the leaves is increased; if the sign is negative, the divergence is diminished.

**404. The Electric Charge Is Found on the Outside of a Conductor.** Fig. 384 shows a silk bag devised by Michael Faraday. If it is electrically charged and then tested with a proof-plane, the outside *only* shows signs of the electric charge. The bag may then be turned inside out by pulling on the string *A*. If it is tested again for electrification, we find in this case too that the charge resides on the outside of the bag.

A hollow sphere open at the top may be used to illustrate the same fact. The electrical charge may be applied to the inside of the sphere. If we apply a proof-plane to the inside and then to an electroscope, there is no evidence of an electri-

cal charge. When the proof-plane is applied to the outside of the hollow sphere, it will be electrified. *The electric charge always resides on the outer surface of a conductor.* This is indeed just what we might expect, if we remember that the object is charged with the same sign throughout; the like charges repel one another and take up positions on the outer surface of the conductor.

An electroscope may be protected by surrounding it with a wire screen. The electroscope is not influenced by any charged objects which are brought near it, since the charge spreads over the outer surface of the screen.

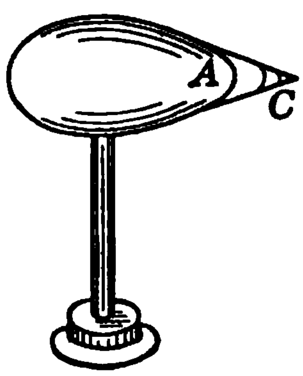



FIG. 385. — Effect of shape on intensity of charge.

**405. The Shape of the Conductor.** By the use of a proof-plane it may be shown that the electrical charge at the pointed end of an egg-shaped conductor, Fig. 385, is more intense than at any other part. The *electrical density, or the quantity of electricity per unit area, is greatest at the point of greatest curvature.* If the small end is made still more pointed, as shown by the dotted lines, the area is decreased and the intensity becomes still greater. At the point $C$ the intensity becomes so great that electricity readily escapes into the air. The air particles are electrified and then repelled with sufficient velocity to produce what is termed an *electrical wind.* Such leakage of electricity from points on the surface of a charged object is generally spoken of as the *discharging effect of points.*

**406. Electrical Pressure.** In the study of fluids we learned that liquid pressure is directly proportional to the depth. Suppose we have an apparatus like that shown in Fig. 386. If one arm is filled with water to the level $A$, pressure is exerted against the stop-cock $K$. Pouring in more water increases the pressure. If the stop-cock is opened, water flows from $A$ into $B$ until it stands at the

same height in both arms; the pressures are now equal. The rate of flow depends upon the difference of pressure in the two arms and the size of the opening in the stop-cock. The larger the opening the less resistance it offers to the current.

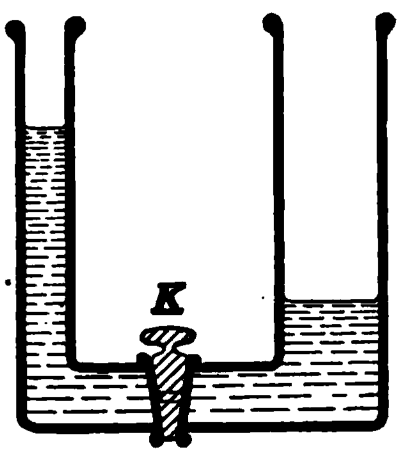


FIG. 386. — Water pressure analogy.

Given two metal balls, separated by an air-gap, as in Fig. 387. If the ball *A* is electrically charged, pressure is exerted, analogous to the water pressure at *A* in Fig. 386. The more intense the charge the greater the pressure. The air-gap is an insulator, acting in the same manner as the stop-cock; hence no current flows to the ball *B*. If we join *A* and *B* by a copper wire, the resistance is decreased and a current of electricity flows to *B* until both *A* and *B* have the same electrical pressure. Analogous to the flow of water, the strength of the current depends upon the difference of pressure between the two balls and upon the resistance of the wire. *An electric current may be defined as an electric charge in motion. The unit of current strength is the ampere. The unit of electrical pressure is the volt, and the unit of resistance is the ohm. Under a pressure of one volt, a current of one ampere will flow through a resistance of one ohm.*

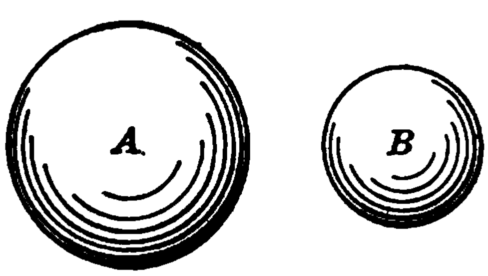


FIG. 387. — Electrical pressure.

In static electricity the energy is potential; in current electricity the energy becomes kinetic. Electrical pressure, or voltage, is often spoken of as *electric potential.* The earth is considered zero potential. An object whose potential is higher than that of the earth is considered positive, or plus; if its potential is lower than that of the earth, it is considered negative, or minus. *The available pressure is always equal to the difference in potential.*

**407. Condensers.** If a metal plate is connected to one of the terminals of an electrical machine, it may be charged to a certain capacity or intensity. When its capacity is reached, the electricity escapes to the surrounding air as fast as it is received. Suppose we bring near this plate a second one which is grounded (connected with the earth), as in Fig. 388. Electrons from the earth are attracted to the second plate. These electrons hold the positive charge on the first plate "bound," and thus prevent their escape. In this way the capacity is increased many fold. *Two conductors separated by an insulator or dielectric form a condenser.* A condenser increases the capacity of a conductor without decidedly increasing its area.

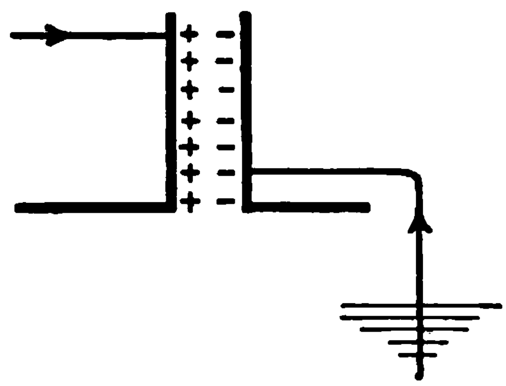


Fig. 388. — Simple condenser.

A more efficient condenser can be made by connecting to one binding post several layers of tin-foil. See Fig. 389. To the other binding post we connect alternate layers of foil, all carefully insulated with paraffined paper.

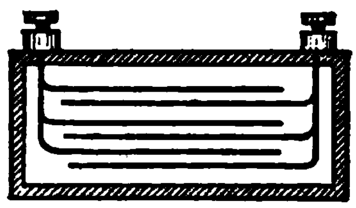


Fig. 389. — Tin-foil condenser.

**408. The Leyden Jar.** Fig. 390 represents a familiar type of condenser which has been known for a long time. A glass jar is coated about halfway up, inside and outside, with tin-foil. A knobbed brass rod extends through the stopper; the lower end of the rod is connected to the inner surface by a brass chain.

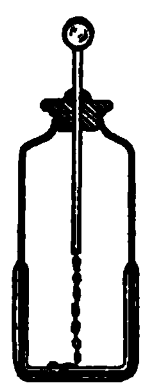


Fig. 390. — Leyden jar.

To charge the jar we connect the knob with the terminal of an electrical machine; the outer coating may be connected with the other terminal of the machine, or it may be grounded by holding the jar in the hand. In the latter case it is connected with the earth through the human body. The capac-

ity of a large Leyden jar is sufficient to give a fairly severe shock when the two surfaces are touched simultaneously. The jar may be discharged in this manner or by merely touching the knob when the jar stands on the table. Why? It may also be discharged by placing one end of a bent conductor in contact with the outer surface and then bringing the other end close to the knob of the Leyden jar.

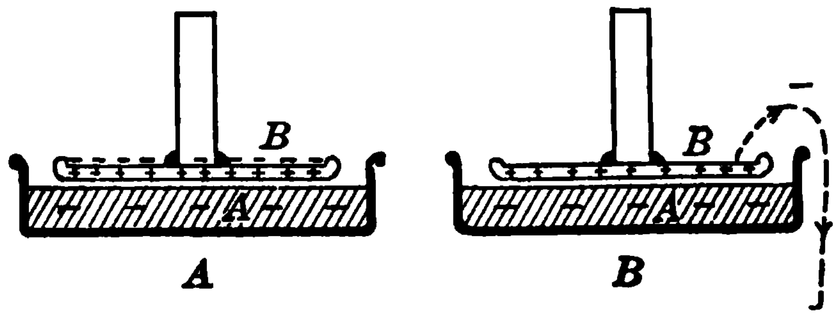



FIG. 391. — Charging an electrophorus.

**409. The Electrophorus.** The electrophorus, shown in Fig. 391, is a device for producing electricity by induction. The bed *A* is composed of vulcanite or some other insulating material. *B* is a metal disc fitted with an insulated handle. When the vulcanite bed is struck several times with a piece of catskin or other fur, it is negatively charged. When the disc is placed on the vulcanite bed, they are in contact at a few points only. Therefore the bed is charged by induction and not by conduction. On the lower surface of the disc there is a positive charge; on the upper surface the charge is negative. See Fig. 391 *A*. When the disc is touched with a finger, as in Fig. 391 *B*, electrons are repelled to the earth, but the positive electricity is "bound" by the negative charge of the vulcanite bed.

If the disc is lifted and a knuckle held near its edge, a short electric spark may be drawn from it. By returning the disc to the bed, touching it again, and then lifting it, a spark may be obtained just as before. The operation may be repeated several times without recharging the vulcanite bed.

**410. Induction Machines.** Several machines that generate electricity by induction have been devised. Fig. 392 shows a diagram of the Wimshurst electrical machine. When the terminals are separated, this machine builds up

a very high potential difference. If the voltage or pressure becomes sufficiently high, the electrical energy will break across the air-gap, producing an electrical spark. To produce a spark only 1 cm. long requires a pressure of about 27,000 volts. It is not uncommon to find static or induction machines which produce a spark several inches long. While the voltage is very high, yet the current which would flow continuously if the terminals were joined is very small. Induction machines are used for demonstration purposes in the laboratory and sometimes for operating X-ray tubes.

Fig. 392. — Wimshurst electrical machine.

**411. Lightning.** It is easy to conceive that the pressure at *A* in Fig. 386 might be increased to such an extent that the stop-cock would give way, or that leakage might occur. In Fig. 387, we can imagine the pressure on ball *A* becoming great enough to force the electricity across the air-gap to ball *B*. This is exactly what occurs when a spark is produced by an induction machine. When such an electrical discharge occurs, the electricity is said to "break down the insulator, or the dielectric."

The winds blowing over the surface of the earth, and the evaporation of water and the condensation of its vapor are believed to be causes of atmospheric electricity. In this way one cloud may be charged with a higher potential than another cloud, or than the earth. If the difference of potential becomes sufficiently great, an electrical discharge takes place between two clouds, or between a cloud and some object on the earth's surface. In the latter case, we say

the object is "struck" by lightning. When Benjamin Franklin flew a kite during a storm and succeeded in drawing sparks from a key fastened to the end of the kite string, he proved that the lightning flash and an electrical discharge are identical. Franklin's experiment is a dangerous one, and should not be tried by students.

**412. Lightning Rods.** Since the heating effects of lightning are very great, metal rods are often used to protect buildings. The statistics compiled by fire insurance companies show that lightning rods which are properly installed are a real protection, but that improperly installed rods are a menace. The rod should be made of some good conductor, although an iron rod seems to be as satisfactory as one of copper; the rod should be thick enough to carry the electric current without melting; lightning rods should extend a slight distance above all the high points of a building, and the lower end should be buried deep enough to be always in contact with *moist* earth. There is some difference of opinion concerning the insulation of rods from the building. Both methods of installation are used. For ordinary buildings it is probably better to insulate the rods to prevent lateral discharge, unless the rod runs close to a waterpipe or gaspipe. Then they should be connected with the pipes by metal conductors. Metal roofs and gutters should all be joined and then grounded.

**413. Magnetism and Electricity.** There are several points of resemblance between electricity and magnetism: (1) the laws of attraction and repulsion are the same in both cases; (2) either one may be produced by induction; (3) there are magnetic fields of force and electrical fields of force; (4) magnets have plus and minus poles; there are two kinds of electricity, plus and minus. Electricity is often used to produce a magnetic effect, and magnetism is very often used to produce electrical energy. The chief differences between magnetism and electricity are as follows: (1) electricity may be

transmitted along a conductor, but magnetism cannot be so conducted; (2) only a few materials can be magnetized, while any substance can be electrified.

## SUMMARY

Electricity may be produced in any object by friction. It may also be *induced* in an object by bringing near it a charged object.

Electricity is of two kinds, positive and negative. Like charges repel; unlike charges attract.

An electroscope is used to detect the presence of an electric charge, to determine its sign, or to measure its intensity.

Conductors transmit electricity readily; insulators, or dielectrics, are poor transmitters.

The electric charge resides on the outside of a conductor. It has its greatest density where the curvature is greatest.

The volt is the unit of electrical pressure; the unit of current strength is the ampere; the unit of resistance is the ohm.

A condenser is used to increase the capacity of a conductor. The Leyden jar is a common example.

Lightning is a violent electrical discharge. Metal rods are often used to protect buildings against lightning.

## QUESTIONS

1. How could you electrify a metal rod?

2. Why do the leaves of a pencil pad often stick together after one has been writing rapidly for some time?

Fig. 393. — Electric whirl.

3. Why do experiments with static electricity work better on clear, dry days?

4. If the little device shown in Fig. 393 is placed on a glass plate and then connected to one terminal of a static machine, the top part whirls rapidly when the machine is in operation. Explain.

5. Why should a lightning rod end in several points? Why is a tall tree near a dwelling house an excellent protection against lightning?

6. Would a large wire screen put over a dwelling house be an efficient protection against lightning? Do you think the steel frame-work of large city buildings furnishes protection?

**7.** Why must a proof-plane have an insulated handle? Does a proof-plane lose all its charge when it is touched to the knob of an electroscope?

**8.** Compare a magnet and a charged rod, giving as many points of similarity as you can and as many differences.

**9.** Is attraction or repulsion the more reliable test for electrification? Explain.

**10.** Why is it impossible to charge a Leyden jar appreciably if it stands on an insulator?

**11.** When a Leyden jar is attached to each of the terminals of a static machine, the spark produced when the discharge occurs is much thickened. Explain why the Leyden jar "fattens" the spark.

**12.** Is the continued use of the electrophorus an example of perpetual motion? If not, what is the source of energy?

**13.** Place the base of a Bunsen burner against the outer coating of a charged Leyden jar. Turn on the gas and then bring the end of the burner tube near the knob. The gas will probably be lighted. Explain.

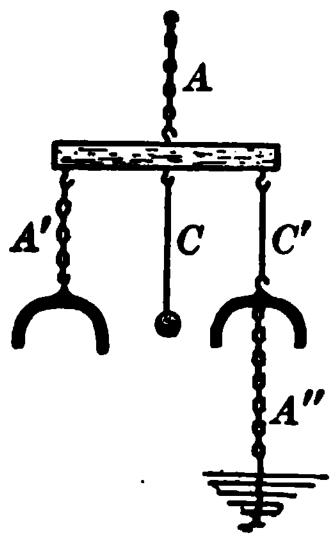


FIG. 394. — Bells.

**14.** Support the apparatus shown in Fig. 394 and connect it with one of the terminals of a static machine. $C$ and $C'$ are silk threads; $A$, $A'$, and $A''$ are brass chains. Why do the bells ring when the machine is in operation?

*Suggested Topic.* Work of Benjamin Franklin.

## CHAPTER 23

# ELECTRICITY — VOLTAIC CELLS

**414. Introductory.** Water at rest has potential energy but it is not doing any work; such is the case with frictional or static electricity. When water begins to flow, its energy becomes kinetic and it may do work. An electric charge in motion has kinetic energy and it may do work. There is no essential difference between static electricity and current electricity, since static electricity produces an electric current when it moves along a conductor; the electric current may also be used to charge objects with different potentials. Before an electric current can be produced there must be some method of building up a difference of potential between two terminals; then when the terminals are joined by a conductor, an electric current is produced. The amount of current produced by a static machine is so small that it has little practical value. Nearly all the electricity used for commercial purposes is now produced by the dynamo, a machine which we shall study later. Formerly the voltaic cell was used very extensively, so much so that *current* electricity is often called *voltaic* electricity. Voltaic cells are now used when a small amount of electricity is needed, usually for a short time only.

**415. The Voltaic Cell.** A *voltaic cell consists of two dissimilar elements immersed in a fluid which acts chemically on one of them.* Zinc is an inexpensive metal that is readily acted upon by acids; it is generally selected as one of the elements. Either carbon or copper is generally used as the other element. If we put a strip of zinc and a carbon rod

**Alessandro Volta** (1745–1827) was a distinguished Italian physicist. He is the inventor of the electric battery, or the voltaic cell. His other inventions include the electrophorus, the electroscope, the electrometer, and the electrical condenser The unit of electrical pressure, the volt, is named in his honor.

**Georg Simon Ohm** (1787-1854) was a German physicist. In his study of the relative conductivity of metals, he discovered the relation between voltage, resistance, and current strength. Ohm's law is fundamental in all electrical theory and measurement. In 1842 Ohm was elected Professor in the University of Munich.

into a tumbler of hydrochloric acid, the acid attacks the zinc, forming zinc chloride and liberating hydrogen. An electroscope test shows that the zinc strip is negatively charged; the carbon rod is positively charged. See Fig. 395. If we join the two elements by a conductor, a current will flow continuously. Joining the elements is called "making" or "closing" the circuit. Disconnecting the conductor is called "breaking" the circuit; the cell is then on *open circuit.* It is customary to speak of the current as flowing from the positive element to the negative through the conductor, or *external circuit.* In the cell (*internal circuit*) the current flows through the liquid from the negative to the positive element. The element that is acted upon in any voltaic cell is called the *negative plate;* the other element is the *positive plate.*

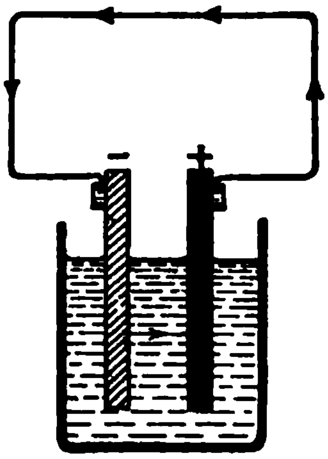


FIG. 395. — Simple voltaic cell.

**416. Theory of the Action in a Voltaic Cell.** In the cell described in the preceding paragraph the hydrochloric acid molecule is composed of one atom of hydrogen, H, and one atom of chlorine, Cl. Its chemical formula is HCl. According to the ionization theory proposed by Arrhenius, HCl *dissociates* in water solution into ions. *An ion may be defined as an atom or a group of atoms carrying an electric charge.* The H ion carries a plus charge and the Cl ion a negative charge, indicated as follows: $H^+$ and $Cl^-$. See Fig. 396. Before the strip of zinc, Zn, is put into the acid solution it is neutral; when it is introduced, the $Cl^-$ ions immediately begin to pull *plus* zinc ions into solution. The loss of these *plus* zinc particles leaves the zinc strip negatively charged. The excess of plus zinc ions around the zinc strip causes the

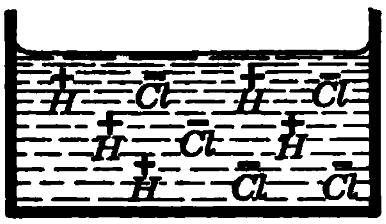


FIG. 396. — Ionization of hydrogen chloride.

plus hydrogen ions to be repelled to the neutral carbon rod. As they come in contact with the rod, they give up their charge, and are liberated as bubbles of hydrogen gas. The $H^+$ ions in this way charge the carbon rod positively. See Fig. 397. On *open circuit* this action continues until the plus charge on the carbon exerts enough back pressure to repel the similarly charged hydrogen ions with a force equal to their repulsion by the zinc ions. This occurs in the case of carbon and zinc when the difference of potential is about 1.5 volts. The pressure differs with other combinations of elements. On *closed circuit* there is a fall of potential along the conductor; the chemical action going on all the time builds up a potential difference between the two elements continuously until the zinc is all dissolved or the acid spent. Therefore, *a voltaic cell transforms chemical energy into electrical energy.*

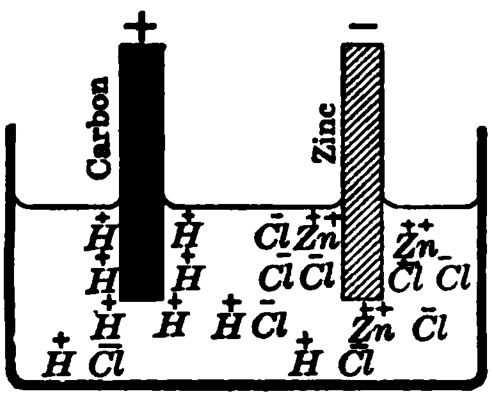



FIG. 397. — Action in voltaic cell.

**417. Defects of a Voltaic Cell.** There are two common defects of a voltaic cell: (1) local action; (2) polarization.

*Local action.* The term "local action" refers to chemical action in a voltaic cell that does not contribute anything to the external circuit and is therefore wasted energy. It is due to carbon impurities in the zinc. Fig. 398 illustrates what occurs when these carbon particles are liberated as the zinc dissolves. These impurities are not dissolved; hence they become positively charged and set up miniature circuits in the cell itself. If we amalgamate the zinc by rubbing its surface with mercury, pure zinc will be dissolved and brought to the surface. The impurities are not dis-

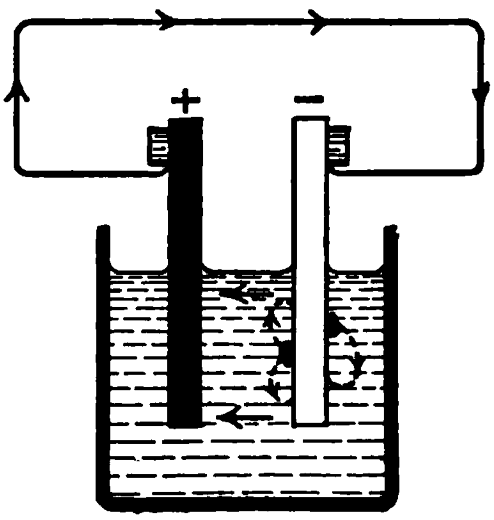



FIG. 398. — Local action.

solved by the mercury, neither are they set free; hence the carbon particles are covered up and local action is prevented. When pure zinc is used for the negative plate, no local action occurs, but chemically pure zinc is expensive.

**418. Polarization.** When a voltmeter, which is an instrument used to measure electrical pressure, is connected to a cell like that described in § 415, it shows a reading of about 1.5 volts. As the cell stands a few minutes on closed circuit, the voltage gradually falls. The cell is now *polarized. Polarization, which causes the fall in voltage, is due to the accumulation of hydrogen bubbles on the positive plate.* When a cell is polarized, the hydrogen bubbles are virtually substituted for the material of the positive plate. Such a hydrogen plate does not give as high a voltage when used with zinc as the carbon plate does. The internal resistance of the cell is also increased.

Fig. 399. — Polarization.

To prevent polarization some chemical must be used to destroy the hydrogen that collects on the positive plate or to prevent any hydrogen from reaching the plate. If we put a crystal of potassium dichromate into the polarized cell of Fig. 399, and stir it to promote solution, the voltage rises to its original value. The oxygen from the dichromate oxidizes the hydrogen, forming water. Chromic acid, nitric acid, and manganese dioxide are chemicals used in various types of cells to destroy the hydrogen and thus prevent polarization.

In the *gravity cell*, or crow-foot, a positive plate of copper is put at the bottom of the cell in a strong solution of copper sulphate; the negative zinc plate is placed near the top of the cell in a dilute solution of zinc sulphate. See Fig. 400. The lighter solution of zinc sulphate floats upon the heavier

solution of copper sulphate. When the cell is in use, copper ions from the copper sulphate carry the positive charge to the copper plate. Since the plate thus becomes coated with a layer of copper instead of hydrogen gas bubbles, its nature is unchanged. Such a cell does not polarize.

Fig. 400. — Gravity cell.

In the *Daniell cell* the plates and solutions used are the same as in the gravity cell. The zinc plate is placed in a solution of zinc sulphate in a porous cup. See Fig. 401. The copper plate is bent into a cylindrical shape; it is placed around the porous cup and immersed in a solution of copper sulphate. The porous cup prevents the mixing of the two liquids. By electro-chemical action, copper is deposited on the positive plate. The Daniell cell is non-polarizing. It gives a very constant voltage.

**419. Types of Cells.** Dozens of cells have been devised, differing from one another in the elements used as plates, in the solution or solutions used, and in the plan used to prevent polarization.

We have already learned that the *gravity cell* and the *Daniell cell* are non-polarizing cells. Their voltage is low, only about 1.1, and they furnish very little current, usually less than one ampere. Unlike most cells, they work better on closed circuit.

In several cells the solution used is chromic acid; the elements are carbon and zinc.

Fig. 401. — Daniell cell.

*Chromic acid cells* give a pressure of about 2 volts, which is fairly constant for a short time. To prevent waste the zinc must be removed from the acid solution when the cell is on open circuit.

At the present time the *dry cell* is the most widely used. It is a modification of the *Lelanché cell*, Fig. 402, which uses carbon and zinc plates immersed in a saturated solution of ammonium chloride, or sal ammoniac. In the dry cell a rod of carbon is placed inside a zinc cylinder which is lined with heavy pasteboard; the space between is packed with a paste of ammonium chloride, manganese dioxide, zinc chloride, powdered coke, graphite, and water, Fig. 403. The top is then sealed with pitch or wax to prevent evaporation. The dry cell gives a large current for *periodic* use. It polarizes to some extent when used continuously, but it recovers when it stands on open circuit. The manganese dioxide and the zinc chloride are used as depolarizers. It is used for ringing door-bells, operating spark-coils for ignition work in gas engines, and for other *intermittent* work.

Fig. 402. — Leclanché cell.

**420. Electrical Units Defined.** We know that the *volt* is that unit of electrical pressure which causes a current of one ampere to flow through a resistance of one ohm. Unfortunately, several terms are used which have practically the same meaning as voltage. Electrical pressure, voltage, and electromotive-force (E.M.F.) are all used almost interchangeably. These terms are used just as

Fig. 403. — Dry cell, sectional view.

engineers use the expression "water-head" to indicate water pressure. Potential difference (P.D.) is often used to indicate the difference in voltage between two points in an electrical circuit. The Clark cell is the legal standard for determining voltage in the United States. At 15° C. it gives 1.434 volts. The Weston cell is also widely used as a standard.

The *ampere*, which is the unit of current strength, is defined in terms of the effect it produces. When a current of one ampere flows through a solution of a silver salt, it deposits 4.025 gm. of silver per hour, or 0.001118 gm. per second. The ampere is sometimes defined in terms of the magnetic effect it produces.

The *ohm* represents the friction encountered by the electric current. It is defined as the resistance offered to the passage of an electric current by a uniform column of mercury 106.3 cm. long, cross-sectional area 1 sq. mm., at a temperature of 0° C.

**421. Ohm's Law.** Let us refer again to § 406. It is obvious that the amount of water that will flow from $A$ to $B$ depends upon the difference of pressure between the two, and upon the resistance offered by the stop-cock. It also follows that the amount of electric current flowing from $A$ to $B$ increases as the difference in voltage increases; the amount of current also decreases as the resistance between the two balls increases. Ohm was the first to state these observations in the form of a definite law. Ohm's law, which is one of the most important truths pertaining to electricity, may be stated as follows: *The current flowing in a circuit is directly proportional to the difference in pressure in volts and inversely proportional to the resistance in ohms.* Therefore,

$$\text{current (amperes)} = \frac{\text{pressure (volts)}}{\text{resistance (ohms)}}.$$

Stated algebraically,

$$I = \frac{E}{R}, \text{ or } I = \frac{P.D.}{R}$$

**422. Laws of Resistance.** Several important facts concerning the resistance of electrical conductors have been determined:

(1) *Law of lengths. The resistance of a conductor is directly proportional to its length.* This means merely that 10 ft. of copper wire have ten times as much resistance as 1 ft. of the *same* wire.

(2) *Law of diameters. The resistance of a conductor is inversely proportional to its cross-sectional area, or to the square of its diameter.* Given two copper wires of equal length; the diameter of one of them is 1 mm., and of the other 2 mm. The first has *four* times as much resistance as the second. The student is astonished to learn that a small wire has a higher resistance than a large one. He will find it easier to understand, if he tries to imagine the friction that 500 gallons of water would encounter in flowing through a pinhole opening, compared to the resistance an opening 1 in. in diameter would offer.

(3) *For metallic conductors the resistance increases with the temperature.* The resistance of carbon, non-metals, and solutions of acids, bases, and salts, decreases with a rise of temperature. A carbon filament lamp has less resistance when it is hot. Glass becomes a fairly good conductor when it is heated. Kamerlingh Onnes found that tin and lead immersed in liquid helium (−269° C.) have almost no resistance. A current set up in a small coil of lead wire persisted for several hours with almost no loss in current strength.

(4) *The resistance depends upon the material.* We have already learned that substances differ greatly in the resistance they offer to the passage of an electric current. If we let $K$ represent a *constant* depending upon the material, it is

possible to summarize the laws of resistance in the following formula:

$$R = \frac{Kl}{d^2};$$

$l$ is the length of the conductor in feet; $d$ is the diameter of the wire in *mils*. *A mil equals 0.001 inch.* Engineers sometimes use the term "circular mils" to represent the cross-sectional area of a wire. The circular mil equals the square of the diameter expressed in mils. A wire has a diameter of 0.025 in.; its diameter equals 25 mils; its cross-sectional area equals $(25)^2$, or 625 circular mils. The constant $K$ expresses the resistance in ohms of one foot of wire whose diameter is 0.001 in.; it is the resistance of one mil foot of wire. The following table gives the value of $K$ for a few of the most common conductors:

| | | | |
|---|---|---|---|
| Silver | 9.74 | German silver | 125–196 |
| Copper | 10.38 | Mercury | 616.5 |
| Aluminum | 17.4 | Nichrome | 747.4 |
| Platinum | 58.8 | Manganin | 250–450 |
| Iron | 64.0 | | |

PROBLEM. Find the resistance of 150 feet of No. 24 copper wire (diameter equals 20.1 mils).

*Solution.* We have the following data: length equals 150 ft.; $d$ equals 20.1 mils; and $k$ equals 10.38. Substituting these values in the formula,

$$R = \frac{Kl}{d^2},$$

we get

$$R = \frac{10.38 \times 150}{(20.1)^2}.$$

Whence we find $R$ the resistance equals 3.85 ohms.

**423. The Voltage of Cells.** Let us connect a voltmeter to the terminals of a non-polarizing cell. If we move the plates of the cells nearer together, the voltage is not affected. When we lift one of the plates, the voltage is not affected

as long as the plate touches the liquid. Experiment also shows that the size of the plate does not affect the voltage of the cell. In fact, experiment shows that the *voltage of a cell depends only upon the materials used in its construction.*

**424. Resistance of Voltaic Cells.** In studying voltaic cells, we must consider their *internal* resistance. Just as the resistance of a conductor varies with its length and cross-sectional area, so the internal resistance of a cell is affected. If we move the plates closer together, the liquid conductor between them is shortened and the resistance is correspondingly decreased. By using larger plates the cross-sectional area of the liquid conductor is increased, and the resistance decreased. While the voltage of a cell is not affected by the size of the plates and their distance from one another, yet we can get more current from a cell with large plates placed as near together as possible, because the internal resistance is decreased. The formula representing Ohm's law when applied to voltaic cells becomes,

$$I = \frac{E}{r + R};$$

$r$ is the internal resistance of the cell, and $R$ the external resistance. The maximum current any cell can give equals its voltage divided by its *internal* resistance, the external resistance in such case being zero.

The internal resistance of the various types of cells differs widely. In the dry cell it varies from 0.05 to 0.1 ohms. The maximum current of such a cell would be from 15 to 30 amperes. In the chromic acid cell the internal resistance is from 0.1 to 0.2 ohms; in the gravity and Daniell cells the internal resistance is usually from 1 to 6 ohms. The current such cells can furnish is very small, usually less than one ampere.

**425. Grouping of Cells.** To secure a higher voltage or more current, cells are sometimes grouped in *series* or *parallel.*

Fig. 404 shows how three cells may be grouped in series. The student will note that the positive plate of one cell is connected with the negative of the next and so on throughout the entire group. We may again use the water analogy to show the advantage of such grouping. If we arrange three water tanks as in Fig. 405, it is evident that each tank adds to the water pressure by increasing the depth. Since the water flows through each of the tanks in succession, the resistance is also three times as great. In the same manner *each* cell in *series* grouping increases the electrical pressure or voltage, and also the *internal* resistance. When Ohm's law is applied to series grouping of cells, it is modified as follows:

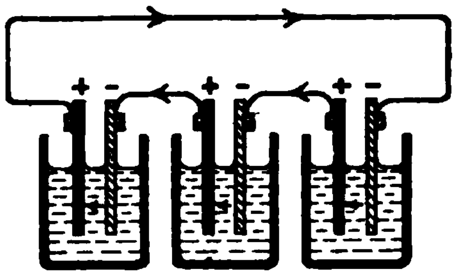


FIG. 404. — Series grouping.

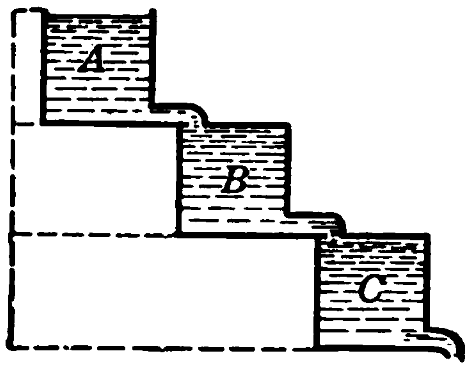


FIG. 405. — Water analogy. Series grouping.

$$I = \frac{nE}{nr + R};$$

$n$ represents the number of cells.

In *parallel*, or *multiple*, grouping the positive plates are all joined to one another; in like manner the negative plates are also connected. See Fig. 406. With parallel grouping the voltage is *not* increased. Suppose we have three tanks of water all at the same level, Fig. 407. Connecting them all to the same external pipe does not increase the pressure, but the resistance is decreased. Only $\frac{1}{3}$ of the water flows from each tank. In the parallel grouping of cells shown,

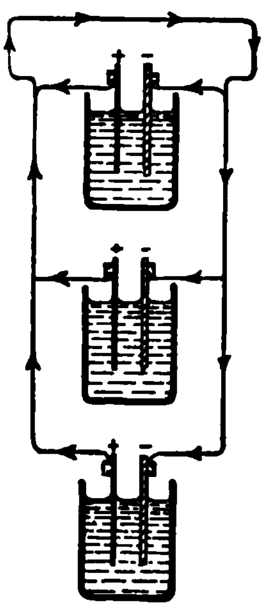


FIG. 406.—Parallel grouping.

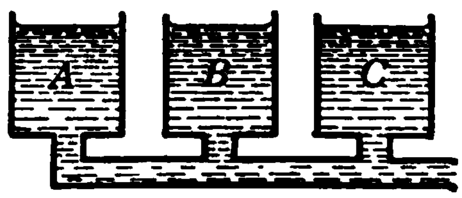


FIG. 407. — Water analogy. Parallel grouping.

only $\frac{1}{3}$ of the current flows through each cell; therefore the internal resistance of any parallel group equals $\frac{1}{n}$ the resistance of a single cell. For parallel grouping, Ohm's law is expressed as follows:

$$I = \frac{E}{\frac{r}{n} + R}.$$

**426. Which Grouping Is Better?** It is possible to test the methods of grouping cells by laboratory experiments. From the results of such experiments, the formulas used above were derived. By solving problems involving the methods of grouping cells, it is easy to find out which method gives the better results.

PROBLEM. Given 20 dry cells, voltage 1.5 each and internal resistance 0.1 ohm. What current will a single cell send through an external resistance of 500 ohms? What current will 20 cells give if they are grouped in series? What current will they produce if they are grouped in parallel?

*Solution.* (*a*) By Ohm's law we find that a single cell furnishes a current of 0.002999 amperes. $\left(\frac{1.5}{0.1 + 500} = 0.002999.\right)$

(*b*) *Series.* Substituting the values in the formula,

$$I = \frac{nE}{nr + R}$$

we obtain the following:

$$I = \frac{20 \times 1.5}{(20 \times 0.1) + 500};$$

whence the current = 0.059 amperes.

(*c*) *Parallel.* By substituting the same values in the formula,

$$I = \frac{E}{\frac{r}{n} + R}$$

we get the following:

$$I = \frac{1.5}{\frac{0.1}{20} + 500};$$

whence $I = 0.002999$ amperes. A single cell furnishes practically the same current when the external resistance is large, as the 20 cells grouped in parallel. The 20 cells when grouped in series furnish nearly 20 times as much current.

PROBLEM. Suppose we have the same cells to be used with an external resistance of 0.005 ohms. What current will the 20 cells in series produce? What current will flow when they are joined in parallel?

*Solution.* The current furnished by a single cell equals

$$\frac{1.5}{0.1 + 0.005}$$

or 14.28 amperes. 20 cells in series will give as many amperes as

$$\frac{20 \times 1.5}{(20 \times 0.1) + 0.005}$$

or 14.9 amperes. If we connect the 20 cells in parallel, the current that may be obtained equals

$$\frac{1.5}{\frac{0.1}{20} + 0.005}$$

or 150 amperes. In the latter case the series grouping yields little more current than the single cell, while the parallel grouping gives more than ten times as much. In the first case the external resistance was large compared with the internal resistance; in the second case the reverse is true.

We may make this general rule to govern cell grouping. If the maximum current is desired, we always use such a combination of cells that the *external* and *total internal* resistances will be as nearly equal as possible. *When the external resistance is large, use series grouping; when the external resistance is small, use parallel grouping.*

## SUMMARY

A voltaic cell consists of two dissimilar plates immersed in a solution that acts chemically upon one of them.

Local action in a voltaic cell is caused by miniature circuits set up between carbon impurities from the zinc and the zinc plate itself. It is usually remedied by amalgamating the negative plate.

Polarization is a defect in a voltaic cell due to the accumulation of hydrogen bubbles on the positive plate. The hydrogen may be destroyed by the use of an oxidizing agent; or, by the use of some mechanical device, it may be kept from coming into contact with the positive plate.

Ohm's law is fundamental; it may be stated as follows: The current in amperes flowing in a circuit is directly proportional to the voltage and inversely proportional to the resistance in ohms.

The resistance of a conductor: (1) is directly proportional to its length; (2) depends upon the material; (3) increases with the temperature in metallic conductors; and, (4) varies inversely as the square of the diameter.

The E.M.F. of a cell depends only upon the materials used in its construction; it is independent of the size or shape of the plates, or of the distance between them.

The current a cell can furnish is directly proportional to its E.M.F.; it is inversely proportional to the internal resistance. Its internal resistance is decreased by using large plates and by placing them near together.

Cells are grouped in series or parallel. Series grouping gives the best results when the external resistance is large; parallel grouping is better when the external resistance is small compared with the internal resistance.

## QUESTIONS AND PROBLEMS

**1.** Which would you use for ringing door-bells, dry cells or gravity cells? Give two reasons.

**2.** A telegraph line is kept on closed circuit when not in use. What type of cell is suitable for such use?

**3.** If a copper wire 0.02 in. in diameter has a resistance of 2.5 ohms per 100 ft., what will be the resistance of 400 ft. of copper wire 0.01 in. in diameter?

**4.** A wire is 0.015 in. in diameter. It is 1000 ft. long. If it is made of German silver ($K = 181$), what is its resistance?

5. If you need a spool of wire having a resistance of 1000 ohms, how many feet of No. 30 German silver wire (diameter = 10 mils) must be used? How many feet of copper wire of the same diameter must be used?

6. A piece of wire 0.1 mm. in diameter has a resistance of 1 ohm. What will be its resistance if it is drawn out until its diameter is only 0.05 mm.?

7. A voltaic cell has an E.M.F. of 1.4 volts; its internal resistance is 0.3 ohms. What current will it furnish when the external resistance is zero? When the external resistance is 0.4 ohms?

8. Incandescent lamps are often operated on a 110-volt circuit. How many dry cells would have to be connected in series to furnish the required voltage? How many Daniell cells? Are lighting circuits usually operated by voltaic cells?

9. A voltaic cell has an E.M.F. of 2 volts; its internal resistance is 0.2 ohms. How should six such cells be grouped to give the maximum current when the external resistance is 5 ohms? Draw a diagram to show the cells thus grouped.

10. What current will the six cells used in problem 9 furnish if they are grouped in series and the external resistance is 0.05 ohms? If they are grouped in parallel?

11. The maximum current of a Daniell cell is reduced just one half when an external resistance of 2 ohms is introduced in the external circuit. What is the internal resistance of the cell?

12. A voltaic cell has an E.M.F. of 1.5 volts; its resistance is 0.08 ohms. Six such cells are joined in series. What current will flow if the external circuit consists of a piece of copper wire 30 ft. long? The diameter of the wire is 15 mils.

*Suggested Topics.* Standard Cells. Edison Lalande Cell.

# CHAPTER 24

# EFFECTS OF THE ELECTRIC CURRENT

## *A.* MAGNETIC EFFECTS

**427. Electricity in Motion Produces a Magnetic Effect.** Oersted found that a magnetic needle is deflected when it is brought near a conductor through which an electric current is flowing. The needle rotates and tends to set itself at right angles to the conductor. See Fig. 408 *a* and *b*. The direction of deflection depends upon the direction in which the current flows. For this reason a compass needle may be used to find the direction in which a current flows. To do so, we make use of the following right-hand rule: *Hold the wire over the compass needle and place the right hand above it, palm downward, with the thumb pointing in the direction the north end of the needle is deflected; the extended fingers now point in the direction the current is flowing.* The relation between the direction of current flow and the deflection of the needle is sometimes expressed as follows: *If one imagines himself swimming with the electric current, facing the magnetic needle, his extended left arm points in the direction of deflection of the north end of the needle.*

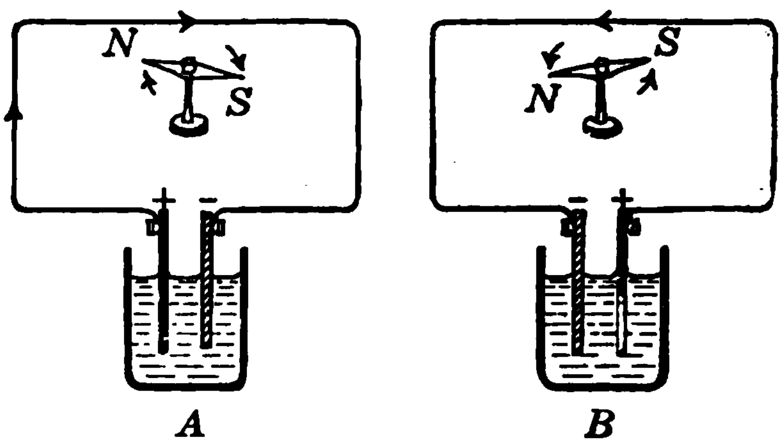


FIG. 408. — Oersted's experiment.

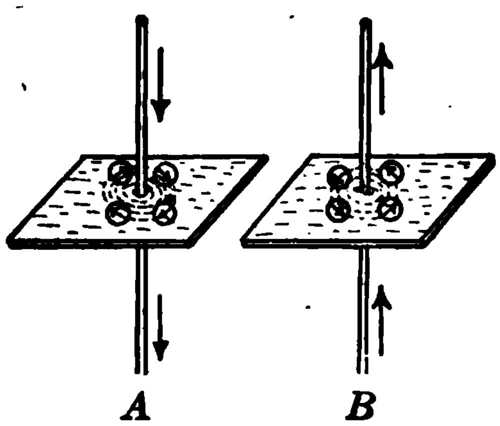


FIG. 409. — Lines of force about a conductor.

**428. Lines of Force about a Conductor.** From Oersted's experiments it is evident that an electric current produces an electrical field in which magnetic lines of force encircle the conductor. Let us pass a vertical wire through a cardboard and place thereon four small compasses. When a current flows through the wire, the compass needles are deflected until they become nearly tangent to the lines of force about the conductor. When the current flows *downward*, the lines of force encircle the conductor in a *clockwise* direction, Fig. 409 *a*. When the current flows *upward*, the lines of force are *counterclockwise*, Fig. 409 *b*. Another right-hand rule may be used to show the relation between the direction of the current flow and the lines of force. *Grasp the conductor with the fingers of the right hand encircling it in the direction of the lines of force; the thumb points in the direction in which the current flows.*

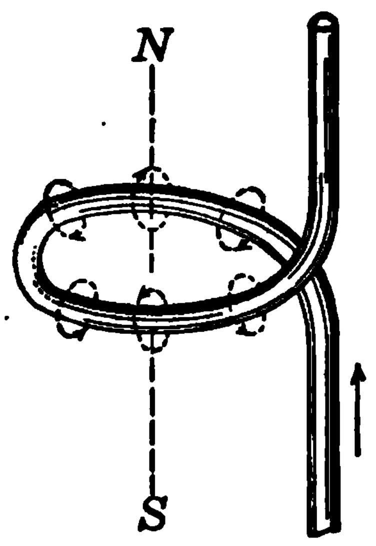



Fig. 410. — Loop of wire a disc magnet.

**429. The Helix or Solenoid.** If we make a loop in a wire carrying a current, *the faces of the loop will show polarity.* If we consider the direction of the lines of force about the wire, the reason for such polarity is obvious. See Fig. 410. The face of the loop toward the observer becomes the north-seeking pole when the current flow is counterclockwise. Reversing the current reverses the polarity.

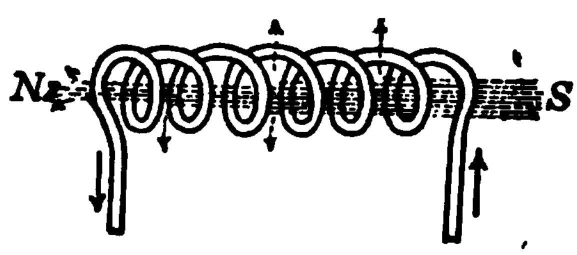



Fig. 411. — Helix.

A *helix* or *solenoid* is formed by winding several such loops in the form of a spiral. See Fig. 411. The polarity is then much more pronounced. Of course each loop becomes a magnet; the whole spiral then acts like a row of disc magnets with their unlike poles adjacent.

**430. The Electro-magnet.** The magnetism of a helix is decidedly strengthened when a bar of soft iron is placed inside, as shown in Fig. 412. Since the iron core is very permeable it affords an excellent path for the lines of force. In Fig. 411 we see how the lines of force tend to stray between the loops of the helix, but the use of the iron core prevents such dissemination of force.

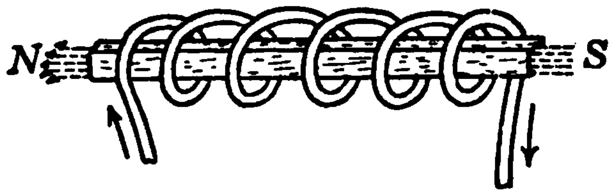


FIG. 412. — Iron bar in helix concentrates lines of force.

Commercial electro-magnets are made by winding a large number of turns of insulated wire on a core of soft iron. They are made in various sizes and forms, but the horseshoe-shaped magnet is the most common. The iron used must be soft enough to lose its magnetism easily. Silicon steel is often used in the cores of magnets. Electro-magnets are temporary magnets, easily magnetized when a current flows through the winding, and retaining only a trace of *residual* magnetism when the current is broken.

The strength of an electro-magnet is increased by increasing the number of turns of wire on the core, and also by increasing the strength of the current. To combine both statements, *the strength of an electro-magnet depends upon the number of ampere-turns.*

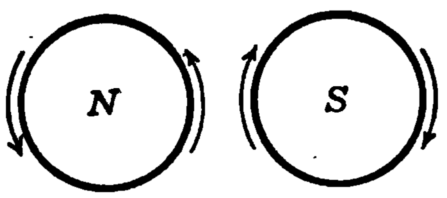


FIG. 413. — Electro-magnet. Polarity.

**431. Polarity of an Electro-magnet.** To find the polarity of an electro-magnet, *grasp the magnet with the fingers of the right hand encircling the magnet in the direction of the current; the extended thumb points to the north-seeking pole.* A horseshoe electro-magnet is so wound that the current will flow in opposite directions around each pole. Just as with the helix, the current flows in a *counterclockwise* direction around the *north-seeking* pole, and in a *clockwise* direction around the *south-seeking* pole, Fig. 413.

FIG. 414. — Lifting magnet. Lifting 8-ton bar of steel.

**432. Uses of Electro-magnet.** The telegraph, electric bell, dynamo, motor, and lifting magnet are all examples of instruments or machines which make use of the electro-magnet. Most electrical measuring machines also make use of the electro-magnet, either directly or indirectly. Lifting magnets are now made so strong that a load of 200 lb. per sq. in. of pole face can be lifted. They are very useful for loading iron and steel billets on cars, for handling steel in steel plants, for lifting kegs of nails, and for other work of like nature. See Fig. 414.

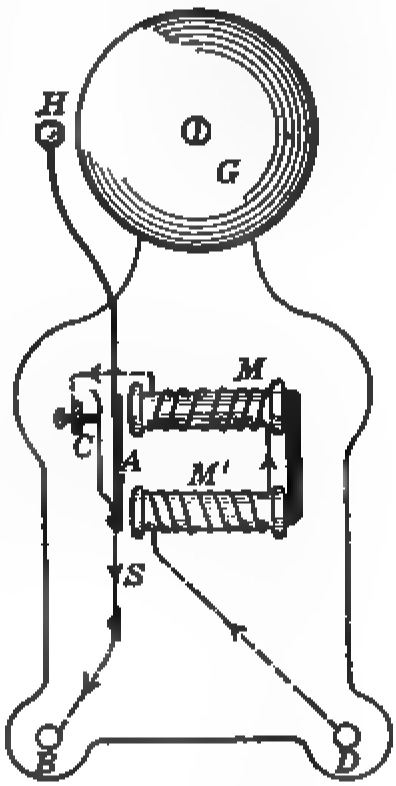



FIG. 415. — Electric bell.

**433. The Electric Bell.** The action of the electric bell may be explained by reference to Fig. 415. *B* and *D* are binding posts to which

**Thomas A. Edison.**

Inventor of phonograph, incandescent lamp, and moving pictures.

**Samuel F. B. Morse.**

Inventor of the telegraph.

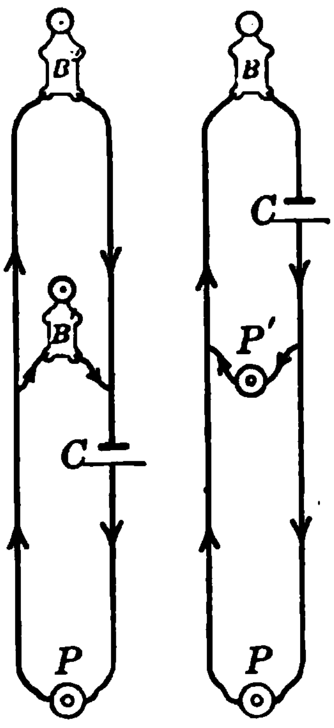
**Alexander Graham Bell.**

Inventor of the telephone.

**George Westinghouse.**

Inventor of air-brake, electrical machines.

the terminals of a voltaic cell may be connected. Suppose the current enters at *D*, flows through the coils of the electro-magnet at *M* and *M′* and returns to *B* by way of the contact screw *C* and the flexible spring *S*. The spring *S* carries a soft iron *armature A*, to which the hammer *H* is attached. When the current flows the magnet *M* is magnetized and attracts the armature so strongly that the hammer strikes the gong *G*. At the same time the bent end of the spring is pulled away from the contact screw at *C*. This breaks the circuit, and *M* loses its magnetism. The spring then forces the armature back to its former position, so that contact is again made at *C*. The circuit is now closed, and the current remagnetizes *M*; the whole operation is then repeated. The spring alternately "makes and breaks" the circuit and the electro-magnet is magnetized and demagnetized, thus causing the hammer to vibrate rapidly.




A B

FIG. 416. — *A*. Bells in parallel. *B*. Two buttons in parallel.

Very often two or more bells are to be used with one push button; or it may happen that two push buttons are to be used with one or more bells. Fig. 416 shows that *parallel* wiring is used to secure such results. In *A* of this figure, if we push the button *P*, the current from the battery divides, part flowing through the bell $B^1$ and part through bell $B^2$. When two push buttons are used, as in *B* of the same figure, the battery must be placed between the bell or bells and the *nearest* push button.

**434. The Telegraph.** The *key*, the *sounder*, the *relay*, the *line wires*, and the *batteries* form the essential parts of a telegraph system.

The *key* is used merely to open and close the circuit. It consists of a brass lever *B*, pivoted on an axis; when the

lever is depressed, the circuit is closed through two platinum or tungsten points. See Fig. 417. When the key is not in use, the line circuit is closed by a switch key $S$.

FIG. 417. — Telegraph key.

In the *sounder* the current flows through an electro-magnet; a brass lever pivoted at $A$, Fig. 418, carries an iron armature $I$. When the sounder is connected to the source of current by means of the binding posts $B$ and $C$, and the circuit is closed by pressing the key, the armature is strongly attracted by the electro-magnet. As the lever is pulled down strongly, it strikes with a sharp click, thus producing the signals which the operator learns to read by sound. When the circuit is again broken, a spring pulls the lever back to its former position.

The *line* consists of rather heavy wires, usually made of galvanized iron. When these wires are strung on poles, they are carefully insulated to prevent grounding. Since the line is often many miles in length, the current may become so feeble that the click of the sounder is indistinct; a *relay* is then used to close a *local* circuit of which the sounder and a *local battery* form a part. The *relay* is merely a circuit closer; it consists of an electro-magnet with a large number of turns of wire. When the electro-magnet is connected with the main line

FIG. 418. — Telegraph sounder.

through the binding posts $A$ and $B$, Fig. 419, it alternately "makes and breaks" the local circuit through the armature simultaneously with the operation of the key. The binding posts $C$ and $D$ are connected in circuit with the local battery and sounder.

FIG. 419. — Telegraph relay.

Fig. 420 shows how the relay, key, sounder, and batteries at one end of the line of a telegraph system are arranged. One end of the line wire is grounded at $G$. At $B$ is the main line battery. When the key $K$ is closed and the key at the other end of the line is in operation, the electromagnet $M$ of the relay simultaneously opens and closes the circuit through the local battery $B'$ and sounder $S$. At the opposite end of the line the instruments are connected in the same manner.

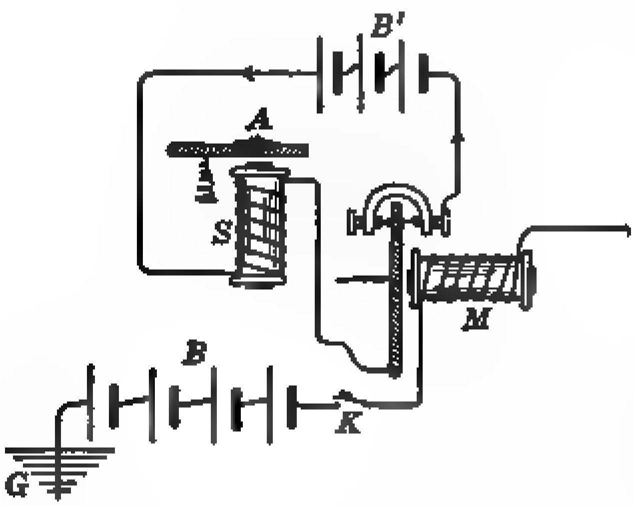


FIG. 420. — Local system, showing key, sounder, and relay.

**435. The Morse Code.** When a telegraph key is pressed and released quickly a short, sharp click is produced; it is known as a "dot." When the key is held for a slightly longer time, the sound is prolonged, producing what is called a "dash." Morse, the inventor of the telegraph, devised a system consisting of combinations of "dots" and "dashes" to represent the different letters of the alphabet. Formerly it was custom-

ary to use a pencil on the sounder lever, by means of which the " dots " and " dashes " were automatically recorded on a strip of paper. Operators at the present time read the message by ear from the " clicking " of the sounder.

## *B.* CHEMICAL EFFECTS

**436. Electrolysis.** When an electric current is passed through the solution of some chemical compound or through the compound in the molten state, a chemical effect is usually produced. The compound is broken up into its component parts. *The decomposition of a compound by means of the electric current is called electrolysis.* The vessel or tank in which electrolysis occurs is called an *electrolytic cell.* In the electrolytic cell of Fig. 421, *A* and *B* are the *electrodes;* that electrode by which the current enters the cell is the *anode;* it is connected to the plus terminal of a battery or dynamo, hence it is *positively* charged. The electrode *B* by which the current leaves the cell is called the *cathode;* since it is connected with the minus terminal of the battery or dynamo, it is *negatively* charged. The solution or liquid through which the current flows is the *electrolyte.*

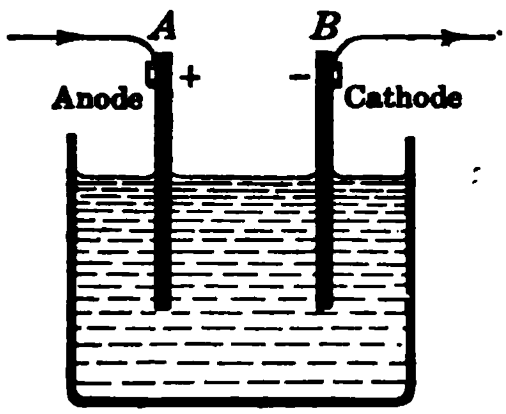



FIG. 421. — Electrolytic cell.

**437. Electrolysis of Water.** Pure water is a poor conductor of electricity, but if a little sulphuric acid is added to the water, the solution which is formed conducts the current fairly well. Sulphuric acid has the chemical formula $H_2SO_4$; when it dissolves in water, a part of its molecules dissociate into hydrogen ions ($H_2^{++}$) which carry positive charges, and sulphate ions ($SO_4^{--}$) which carry negative charges. Suppose we put into such an ionized solution two electrodes of platinum or carbon and connect them to the terminals of a battery of

cells joined in series, as in Fig. 422. Since the cathode is negatively charged, it attracts the $H_2^{++}$ ions, neutralizes their charge, and liberates hydrogen gas. The $SO_4^{--}$ ions are attracted to the anode; when their charge is neutralized, they take hydrogen from the water to form more sulphuric acid. Water is composed of hydrogen and oxygen; when the hydrogen is thus removed by the sulphion ($SO_4^{--}$) group, oxygen is set free at the anode. If we use an apparatus for collecting these gases, Fig. 423, we find that the hydrogen accumulates just twice as fast as the oxygen. When water is thus decomposed, it always yields two volumes of hydrogen to one volume of oxygen. The amount of sulphuric acid is not changed.

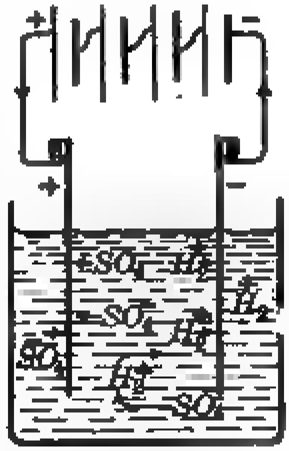


FIG. 422. — Ionization of sulphuric acid.

**438. Electro-plating.** When copper sulphate ($CuSO_4$) is dissolved in water, it dissociates into copper ions ($Cu^{++}$) and the sulphion group ($SO_4^{--}$). For copper plating such a solution is used as the electrolyte. The article to be plated is suspended from the cathode of an electrolytic cell, and a bar of pure copper is used as the anode. The positive copper ions are attracted to the cathode; as their charge is neutralized, metallic copper is deposited as an even coat over the article to be plated. The $SO_4^{--}$ ions are attracted to the copper bar at the anode; as their charge is neutralized, they pull more copper ions into solution, thus keeping the concentration of the electrolyte

FIG. 423. — Apparatus for the electrolysis of water.

nearly uniform. Copper goes into solution at the anode and is deposited on the article to be plated, which really forms the cathode. See Fig. 424.

If we wish to plate an article with silver, we attach it to the cathode; a bar of pure silver is made the anode, and some silver salt is used as the electrolyte. In general, *the object to be plated is made the cathode; a bar of pure metal with which the object is to be plated forms the anode; a salt of the metal, usually a double salt, is used as the electrolyte.* The metal "plating" adheres better if a relatively small current is used during the plating. For depositing metals rapidly the electrolyte is often stirred or agitated. This may be done by a mechanical stirrer, or by rotating either the anode or the cathode. Then more amperage may be used, because the ions are well distributed.

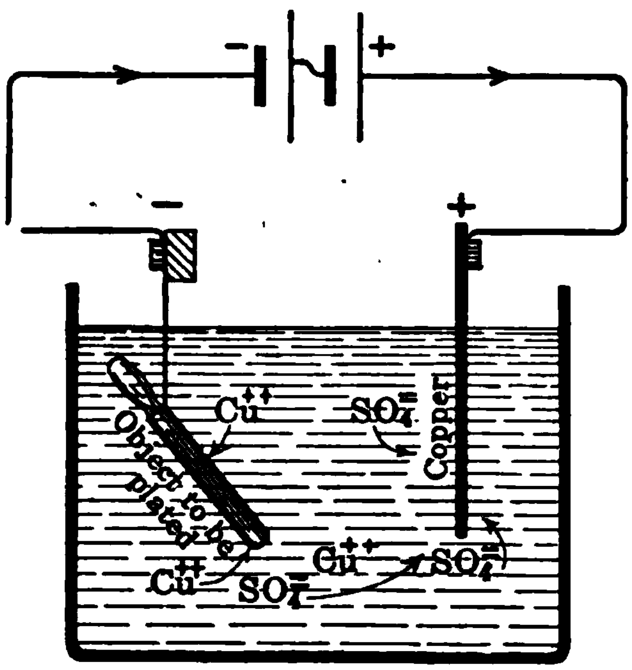


FIG. 424. — Copper plating.

**439. Electro-typing.** Books are usually printed from electrotypes. After the type is set, an impression of each type-page is made in wax. The impression is first covered with graphite to make it a conductor, and then attached to the cathode of a copper-plating cell. When a firm layer of copper has been deposited, it is removed and the wax replaced by type-metal to secure rigidity. Facsimile reproductions of chased ornaments and other works of art are often made by means of electro-typing.

**440. Electro-metallurgy.** Several metals, aluminum for example, are extracted from their ores with considerable difficulty. Where a cheap source of electric current is available, as at Niagara Falls, it is often profitable to extract such

metals by passing an electric current through their molten ores, or solutions of them. The metal collects at the cathode. Certain metals are refined by electrolysis. Copper is purified by using a bar of impure copper as the anode, and pure copper for the cathode. As the impure copper goes into solution at the anode, pure copper is deposited on the cathode. The impurities collect in the electrolyte at the bottom of the tank. Traces of arsenic in copper lower its electrical conductivity about one half; the presence of 0.4 per cent of iron lowers its conductivity 64 per cent; therefore wire to be used for electrical purposes is made from *very pure* copper. Gold and silver are obtained from the "mud" which collects on the bottom of the tank during the refining of copper. They are separated, and then refined by electrolysis. Tin is now purified by electrolysis in American refineries.

**441. Faraday's Laws of Electrolysis.** Faraday found that the amount of any element deposited by electrolysis depends upon several factors: (1) *It is directly proportional to the time the current flows;* a current that deposits one half pennyweight of silver on a table-knife in 10 minutes will deposit one pennyweight if allowed to flow for 20 minutes. (2) *The amount deposited is directly proportional to the strength of the current in amperes.* A current of one ampere deposits 0.001118 gm. of silver per second, and a current of 10 amperes deposits 0.01118 gm. of silver per second. (3) *The amount deposited is directly proportional to the electro-chemical equivalent of the element.* The current that liberates 1 gm. of hydrogen in one hour could in the same time liberate 8 gm. of oxygen, 31.8 gm. of copper, or 107.88 gm. of silver, since these numbers have the same ratio as the electro-chemical equivalents of the elements.

**442. The Storage Cell.** We know that the voltaic cell is used to transform chemical energy into electrical energy. It is sometimes called a *primary* cell. *An electrolytic cell transforms electrical energy into chemical energy.* It is

often called a *secondary* cell. Let us make an electrolytic cell by connecting two lead plates to the terminals of a primary battery or a dynamo, and immersing them in sulphuric acid as an electrolyte. With only one exception the same chemical action occurs as in the electrolysis of water; the oxygen does not escape, but it unites chemically with the lead anode to form lead dioxide ($PbO_2$). Such a cell *stores chemical energy;* it is called a *storage cell.* Since the *similar* lead plates have been made *dissimilar* by the action of the current, the cell should produce an electric current. (See definition of a voltaic cell, § 415.) In other words, electrical energy has been used to make a voltaic cell. If we connect such a cell to a measuring instrument, it shows a pressure of about 2.2 volts. The lead dioxide becomes the positive plate; such a cell furnishes current until all the oxygen of the dioxide plate has been used.

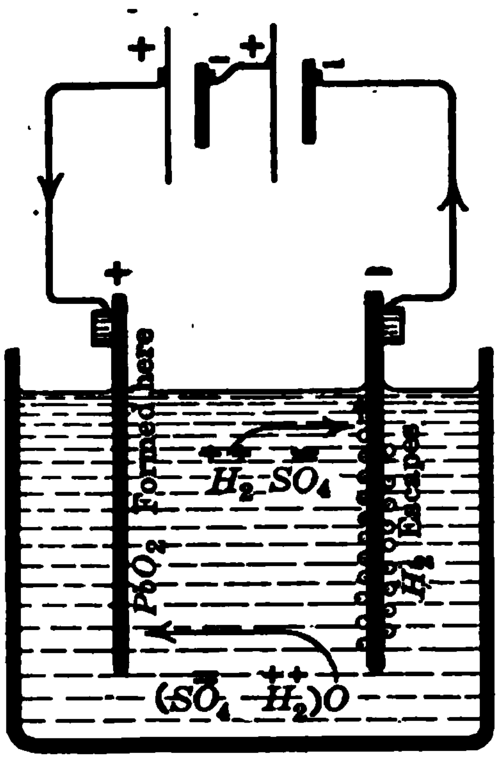
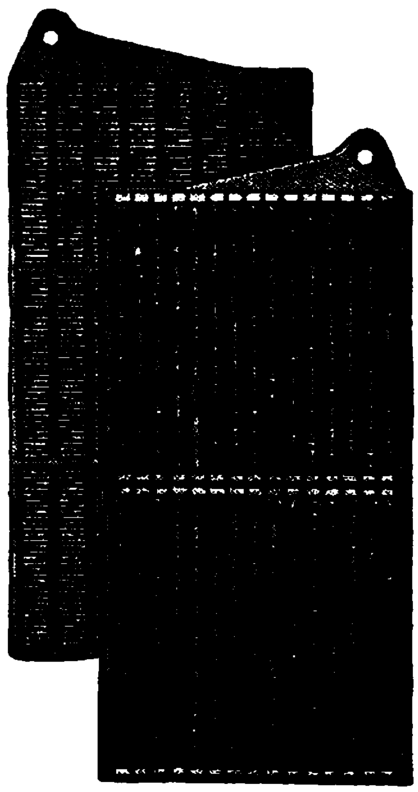



FIG. 425. — Chemistry of storage cell.

In commercial storage cells several lead grids are joined to form each plate. They are grooved and packed with oxides of lead to make them more efficient. Red oxide of lead ($Pb_3O_4$) is packed around the positive plate and litharge ($PbO$) around the negative. In charging the cell, the red lead is oxidized to form lead dioxide ($PbO_2$) and the litharge is reduced to metallic lead. See Fig. 425.



*A* *B*

FIG. 426. — Storage cell. *A*. Negative plate. *B*. Positive plate.

The Edison storage battery uses for the positive plate nickel oxide enclosed in perforated containers made of nickel-plated iron; for the negative plate iron oxide is packed in similar containers (Fig. 426); the electrolyte used is caustic potash or caustic soda. Since the Edison battery is designed

FIG. 427. — Edison storage cell.

especially for traction work, it is made light and very strong. See Fig. 427.

**443. Advantages and Disadvantages of the Storage Cell.** The resistance of the storage cell is very small, and very large currents may be obtained. Fig. 428 shows the positive and negative plates of a lead storage cell. The lead storage cell is heavy and its efficiency is only about 75% under the most care-

Fig. 428. — Plates for lead storage cell

ful usage. It is injured if completely discharged; in fact it should not be discharged so that the pressure falls below 1.8 volts, or lead sulphate will be formed, and "sulphation" of the cells will result. Lead storage cells may be charged and discharged indefinitely; in fact they work better after they have been charged many times. Such cells are injured if they are charged or discharged too rapidly. Fig. 429 shows the arrangement of the plates in a commercial storage cell.

The Edison storage cell is only about half as heavy as the lead cell of equal capacity, but its efficiency is somewhat less. The Edison cell is not easily injured mechanically, and it can hardly be injured by rapid charging or discharging. Its pressure is about 1.25 volts.

Fig. 429. — Lead storage cell.

The storage cell finds extensive use in automobiles and in submarines. It is also used in power stations when the load is very light or to supplement the dynamos when the load is heavy. Such cells also find use in telephone and wireless work. Storage cells are sometimes called *accumulators.*

## C. HEATING EFFECTS

**444. Heating Effects of the Electric Current.** In Fig. 430, $AB$ is a short piece of German silver wire connected by copper wires to the terminals of two dry cells. When the circuit is closed through the contact key $K$, the German silver wire becomes white hot and will probably melt. *Every conductor is heated to some extent by an electric current flowing through it,* since all conductors offer some resistance; we have already learned that resistance or friction produces heat. If the conductor is large and the current small, the amount of heat produced is negligible.

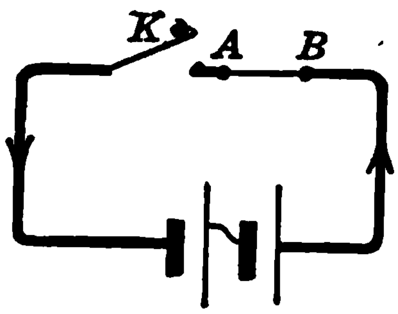


FIG. 430. — Heating effect of current.

**445. Joule's Laws.** A series of experiments which were carried out by James Prescott Joule shows that the amount of heat produced by the electric current depends upon several factors: (1) *That the amount of heat is proportional to the resistance in ohms;* (2) *to the square of the current strength in amperes; and* (3) *to the time the current flows.* From his experiments he derived a formula which furnishes us with a method of determining quantitatively the amount of heat developed in a conductor. In the formula,

$$\text{calories} = I^2R \times t \times 0.24,$$

$I$ represents the strength of the current in amperes, $R$ the resistance of the conductor in ohms, and $t$ the time in seconds.

PROBLEM. The heating coil in a coffee percolator has a resistance of 22 ohms and uses 5 amperes of current. How long will it take to heat one liter of water from 20° C. to the boiling point, 100° C., in such a percolator?

*Solution.* To heat one liter of water (1000 gm.) from 20° C. to 100° C. requires 80,000 calories. Substituting the values in the formula,

$$\text{calories} = I^2R \times t \times 0.24,$$

we have

$$80{,}000 = 5 \times 5 \times 22 \times t \times 0.24;$$

whence $t$ equals 606 seconds, just a trifle more than ten minutes.

**446. Applications.** The *electric flat-iron*, the *bread-toaster*, the *coffee percolator*, the *electric grill*, and the *electric heater*, Fig. 431, are all familiar applications of the heating effects of the electric current. Many trolley cars are now heated by electric heaters. In each of these cases coils of high resistance wire often made of nickel or nichrome are so grouped that a great deal of heat is concentrated at one place. See diagram of the heating coil in an electric flat-iron, Fig. 432. Electric cooking and heating are expensive at the present prices charged for current.

FIG. 431. — Electric heater. (Coils of nichrome wire.)

If two pieces of wire are placed end to end and a current passed through them, the heat developed at their point of contact may be sufficient to *weld* them into one piece. Electric welding is extensively used, especially by trolley companies.

*Fuse wires* are used in electric circuits to protect instruments and machines, and to prevent fires caused by short-circuits. In ordinary electric lighting, the current is fur-

nished at a pressure of 110 volts. Suppose it flows through a lamp having a resistance of 220 ohms; the amount of current is 0.5 ampere. If, by accident, a piece of metal having a resistance of only 1 ohm should connect the two termi-

FIG. 432. — Electric flat-iron. Cut away to show heating coils.

nals, a short circuit is produced, and a very large current flows through the reduced resistance. The decrease in the resistance tends to lower the heating effect to $\frac{1}{220}$ of what it was before, but the current, which is increased 220 times, tends to increase the heat by $(220)^2$. The joint effect increases the amount of heat to 220 times what it was at the beginning. The wire would probably melt and might possibly set fire to any inflammable material near it. To prevent

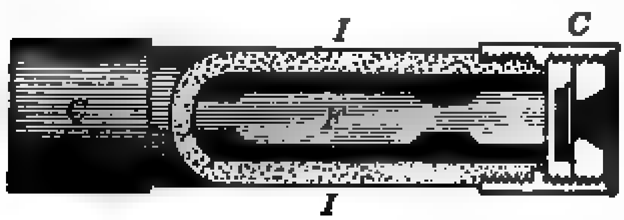


FIG. 433. — Cartridge fuse. Brass contacts are shown at $C$. The fusible metal $F$ is enclosed in insulating material.

such possibility of fires, short pieces of fuse wire are placed in all wiring circuits. The fuse wire has a higher resistance and a lower melting point than the copper wire. Fig. 433. If an overload occurs as a result of a short-circuit

or other cause, the fuse wire melts and breaks the circuit. Fuse wires, Fig. 434, are placed in a closed metal box, so the danger from fires enkindled by the melting of the fuses is eliminated.

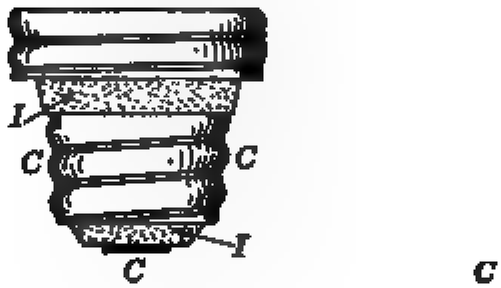



Fig. 434. — Plug fuses. The fusible wire *F* is surrounded by fire-proof material *I*.

**447. Incandescent Lamps.** Electric lighting is merely a practical application of the heating effects of the electric current. In the incandescent lamps some small wire or filament which has a very high melting point is heated until it glows brightly. To prevent oxidation or burning of the filament, it is placed in a glass bulb from which the air is exhausted, or in some cases in a bulb filled with inert gases.

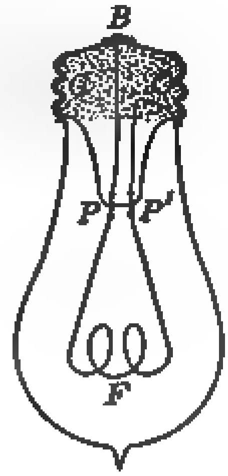



Fig. 435. — Diagram of carbon lamp.

The earliest lamps of this type were invented by Edison; they were first used at Roselle Park, New Jersey. In these lamps a coiled filament of carbon is used, Fig. 435. The ends of the filament *F* are cemented to two short pieces of platinum wire *P* and *P′*. These short wires are connected by copper wires, one to a brass disc *B* which makes contact in the socket with one terminal of the lighting circuit; the other is connected with the threaded cylinder *C* which makes connection with the other terminal of the lighting circuit when the lamp is screwed into the socket. The bulb is exhausted until it is a nearly perfect vacuum. With a 16 C.P. lamp

Fig. 436. — Diagram of tungsten lamp.

of this type the resistance of the filament when hot is about 220 ohms. Such a lamp uses 0.5 ampere of current when used on a 110-volt circuit.

On account of their greater efficiency, metal filament lamps have practically replaced the carbon lamp. The *tungsten* lamp, Fig. 436, is used very extensively. An alloy

Fig. 437. — Tungsten lamp.

Fig. 438. — Gas filled tungsten lamp.

has been found to replace the expensive metal platinum for leading in wires. A 20 C.P. lamp of the tungsten type uses from 0.2 to 0.23 ampere of current when operating on a 110-volt circuit. Therefore it is nearly 2.5 times as efficient as the carbon lamp. Fig. 437. The light from a tungsten lamp is whiter than that from the carbon lamp, more nearly like sunlight. Since the maximum candle power of these lamps is

horizontal, a frosted bulb or a concentrating reflector must be used to secure proper distribution of light.

The gas-filled lamp is a tungsten lamp in which nitrogen or argon is used for filling the bulb, Fig. 438. The long filament is wound in a very close spiral, thus preventing loss of heat by radiation. Since the tungsten does not evaporate so rapidly when surrounded by the argon-nitrogen mixture as in a vacuum, the filament can be heated to a higher temperature. The efficiency of the lamp is thus increased, and the bulb does not darken so readily. Incandescent lamps are generally grouped in parallel. The voltage between the terminals is constant. See Fig. 439.

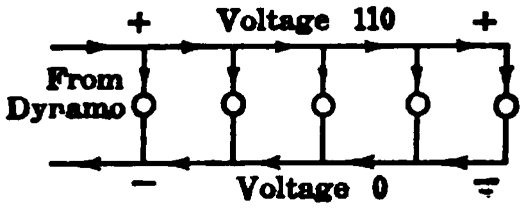



FIG. 439. — Incandescent lamps are wired in parallel.

**448. Arc Lighting.** In the production of the arc light two rods of gas carbon are brought together momentarily and then separated about one fourth of an inch. The resistance at the point of contact is so great that some of the carbon is vaporized by the heat produced. Fig. 440. This carbon vapor serves as a conductor and forms the arc; the light produced is very intense. Arc lamps are generally operated in series, Fig. 441, about 40 lamps to a 2200 volt dynamo. The difference of potential between the two carbons is about 50 volts. The lamp uses from 10 to 25 amperes of current, varying with the size of the carbons. The efficiency of the arc lamp is slightly higher than that of the ordinary tungsten lamp. Except in very large halls

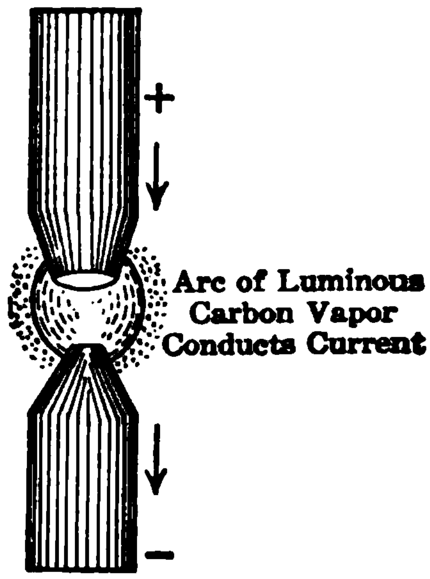



FIG. 440. — Arc lamp carbons.

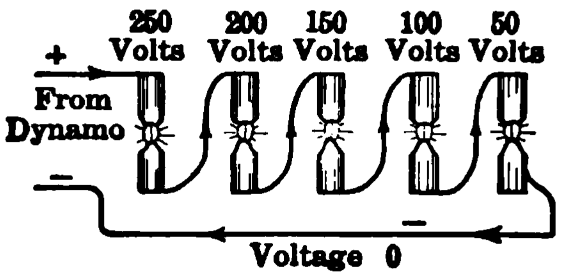



FIG. 441. — Arc lamps are wired in series.

or storerooms, arc lamps are not much used for interior lighting, since they are not efficient in small units.

The *flaming arc* is extensively used for park illumination. The carbons have a core consisting of the salts of certain metals, especially those of calcium and magnesium; the arc is colored by their flame and much more light is produced. They may be nearly four times as efficient as the ordinary arc lamp.

**449. Electric Furnace.** In one type of electric furnace the current passes through a coil of platinum, tungsten, nichrome,

FIG. 442. — A simple electric furnace.

or molybdenum wire which is wound on some very refractory material. A temperature of from 1000° C. to nearly 2000° C. can be obtained with such a *resistance* furnace.

In the *arc type* of electric furnace a temperature of 3500° C. may be obtained. In this furnace the electric arc is produced inside a crucible to melt the contents. Fig. 442. Such electric furnaces are used to make carborundum, calcium carbide, artificial graphite, nitrogen compounds from the air, and high grade steel.

## SUMMARY

An electric current produces a magnetic effect. If we grasp the conductor, with the fingers of the right hand encircling it in the direction of the lines of force, the extended thumb points in the direction of the current flow.

An electro-magnet consists of a soft iron core wound with a number of turns of insulated wire. The strength of the electro-magnet depends upon the number of ampere-turns.

Electrolysis is the decomposition of a compound by means of an electric current. The current enters an electrolytic cell by the anode and leaves by the cathode. Hydrogen and most metals are electro-positive; they are attracted to the cathode. The non-metals, which are electro-negative, are attracted to the anode.

The ordinary storage cell consists of two lead plates immersed in a solution of sulphuric acid. They become dissimilar when an electric current is passed through the cell; two dissimilar plates immersed in an electrolyte produce a difference of potential. No electricity is stored in a storage cell.

An electric current produces a heating effect. The amount of heat produced is proportional to the time, the resistance, and the square of the current strength. Electric lighting is merely a modified application of the heating effects of the electric current.

## QUESTIONS AND PROBLEMS

1. If a helix is supported so it is free to rotate, what position does it assume when a current is passed through it?

2. How could you tell what direction a current is flowing through a wire in the ceiling of a room? If the ends of the wires are exposed, how can you tell which is the positive terminal by dipping the wires into a solution of copper sulphate?

3. Why is an iron core used in an electro-magnet? Would steel do as well? Give two reasons for your answer.

4. What is triple-plated silverware? What does the mark "12 Dwt." mean as used so frequently on silver-plated ware?

5. Draw a diagram to show an apparatus that might be used for plating an object with gold. Label your diagram carefully.

6. How can Faraday's second law be used to determine the strength of an electric current?

7. What is actually "stored" in a storage battery?

8. What is meant by the "carrying capacity" of a conductor? What does the expression "overload" mean?

9. Would you use a 25-ampere fuse plug with a wire which can carry safely only 17 amperes? Explain fully.

**10.** In what two ways may the wiring of a flat-iron be varied to concentrate the heat at the point? What is the advantage of a "hot-point" flat-iron?

**11.** How much is the heat increased if the resistance is doubled and the current unchanged? How much is the heat increased if the current is doubled and the resistance unchanged?

**12.** How much silver will a current of one ampere deposit in 15 minutes? How much copper will the same current deposit in the same time?

**13.** If the resistance of a lamp is 220 ohms and the current is 0.5 ampere, how many calories of heat will it produce in 10 minutes?

**14.** A 3-Kgm. flat-iron uses 4.5 amperes of current when operating on a 110-volt circuit. How long will it take to heat the flat-iron from 20° C. to 200° C., if there is no loss of heat by radiation? The specific heat of iron in 0.113.

**15.** A storage cell charged to its maximum capacity has a pressure of 2.2 volts. Could a single dry cell be used to charge this storage cell? Could it be charged by two cells in series? How many cells in parallel grouping would be required? (E.M.F. of a dry cell equals 1.5 volts.)

*Suggested Topics.* Stock Ticker. Compare Cost of Heating by Coal, Gas, and Electricity. Efficiency of Various Types of Gas and Electric Lights. Cooper-Hewitt Lamps.

# CHAPTER 25

## MEASURING INSTRUMENTS

**450. The Galvanoscope.** One of the simplest measuring instruments used in electricity is the *galvanoscope.* We have seen that a wire carrying a current sets up around the wire a magnetic field which causes a magnetic needle to be deflected. If we make a loop or coil of wire, Fig. 443, and put a needle inside the loop, the deflection is increased. Increasing the number of turns in the coil increases the deflection still more. By using a large number of turns even a feeble current will cause a marked deflection. *Such an instrument may be used to detect the presence of a current or to determine its direction.* Fig. 444 shows a common type of galvanoscope.

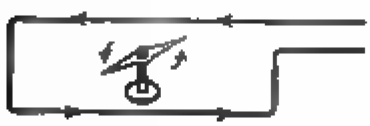


FIG. 443. — Current flowing through loop affects needle.

**451. The Galvanometer.** It is not always sufficient to detect the presence of a current and to determine its direction; we often need to measure the strength of such a current and to find its voltage. For such purposes a *galvanometer* may be used. Several types of galvanometer are in use, but we shall discuss only two of them here, the *movable-needle* and the *movable-coil.* The movable-needle galvanometer is essen-

FIG. 444. — Galvanoscope.

tially a galvanoscope which has been calibrated to show the strength of the current from the amount of deflection. Fig. 445 shows a tangent galvanometer of this type. When the plane of its coils is in the earth's magnetic meridian, the strength of the current is directly proportional to the tangent of the angle of deflection, provided the angle is kept fairly small. If a circular coil of three turns of 10 cm. radius is used, a current of one ampere produces a deflection of about 45° in a small compass needle placed at the center of the coil. Incidentally this furnishes us with a definition of the ampere based upon the strength of the magnetic field which a current of ampere strength can produce.

In the movable-coil type of galvanometer, a coil is suspended between the poles of a permanent horseshoe magnet. The coil, which is really a helix, is magnetized when the current flows through it; its pole-faces are then attracted and repelled by the poles of the permanent magnet. The coil carries a small pointer which moves over a graduated scale as the coil is deflected; in some instruments the coil carries a small mirror which reflects a beam of light to a scale several feet distant, thus magnifying the amount of deflection. Fig. 446 shows a movable-coil type of galvanometer.

Fig. 445. — Tangent galvanometer.

**452. The Voltmeter and Ammeter.** Many *voltmeters* and *ammeters* are galvanometers of the movable-coil type. The coil is mounted on jeweled bearings; the current enters through two springs which hold the coil so that the pointer indicates zero when no current is flowing through the coil, Fig. 447. The voltmeter is calibrated to read volts directly; the ammeter, to read amperes. The two instruments differ very slightly in construction. The *voltmeter* coil consists of a fine insulated wire wound on a light frame called a *former*. This movable coil is connected in series with a *high-resistance* coil so that the difference of potential between the binding posts of the instrument may be as great as possible. The current flowing through the voltmeter must be so small that it does not appreciably lower the difference of potential between the terminals of the instrument. See Fig. 448. The *ammeter* must have a low resistance in order not to increase the resistance of the circuit. It may be wound with a few turns of coarse *low-resistance* wire; more often the winding is the same as that used for the voltmeter, but a *low-resistance shunt* is connected across its terminals. Therefore its resistance becomes almost negligible. Trace the current through the wiring diagram of Fig. 449 when it is used as an ammeter. Note that the ammeter is connected in

FIG. 446. — Movable coil galvanometer.

series. Trace the current when the voltage button is pressed down. The voltmeter is in parallel. Since an ammeter is always connected in series in a circuit, the resistance it offers must be so small that the current flow which we wish to measure is not reduced by the ammeter itself.

FIG. 447. — Magnet and coil for voltmeter.

**453. Fall of Potential along a Conductor.** A voltmeter shows the *difference of potential*, or the *effective pressure* between two points of a circuit. Suppose a voltmeter connected directly to the terminals of a storage cell shows a P.D. of 2 volts. Let us next connect the terminals of this cell with a uniform wire 12 ft. long and then test with a voltmeter the difference of potential between different points along the wire. The results of our experiment show that the fall of potential along the wire conductor is gradual. See Fig. 450. Between $A$ and $B$ (6 ft.) the drop of potential is one volt, and between $B$ and $C$ (3 ft.) it is only 0.5 volt.

If the external resistance is not uniform, the fall of potential occurs, but it is not gradual. Suppose the dynamo of Fig. 451 maintains a constant P.D. of 50 volts between $A$ and $C$; the resistance of $AB$ is 8 ohms and the resistance of

FIG. 448. — Voltmeter.

*BC* is 2 ohms. The total resistance is 10 ohms, therefore a current of 5 amperes flows through the circuit. In order that 5 amperes may flow through *AB*, 8 ohms resistance, the P.D. between these points must be 40 volts. The P.D. between *B* and *C* must be 10 volts to send 5 amperes of current through 2 ohms resistance. From a consideration of these

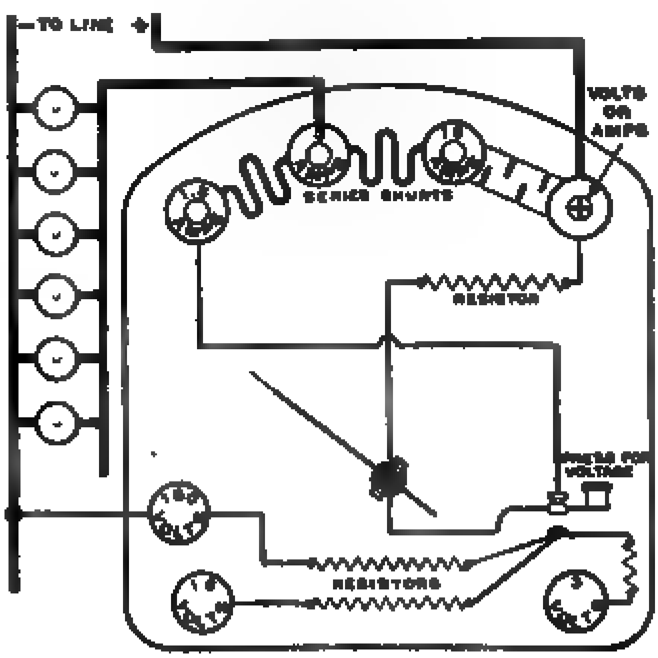



FIG. 449. — Voltmeter and ammeter diagram.

cases, it is evident that the *fall of potential in a circuit is proportional to the resistance,* since $40:8=10:2$. The student should remember that the current in all parts of a series circuit is uniform. In Fig. 452 it is obvious that no more water can flow through the large pipes *B* and *C* than through the pipe *A*.

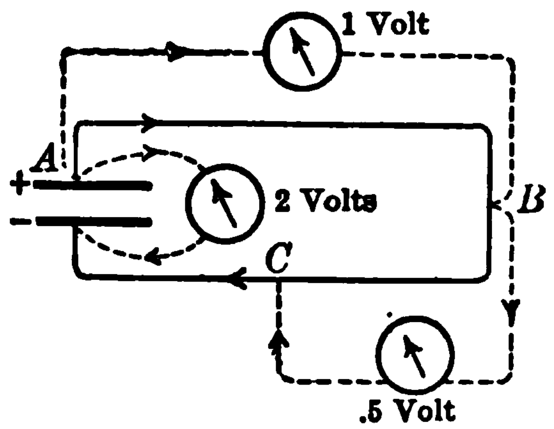



FIG. 450. — Fall of potential, resistance uniform.

**454. Rheostats or Resistance Coils.** Rheostats, or resistance coils, are sometimes used to measure resistance; more often they are used to reduce the voltage in some part of a circuit, or to reduce the amperage. They consist of coils of high resistance wire which are so arranged that one or more coils may be thrown into the circuit in series. Fig. 453 shows how this may be accomplished. When the brass plug *P* is inserted the current flows through the brass strips *BB′* instead of through the coil *C*, which has much greater resistance. When the plug from *D* is removed the current then flows through the coil *C′*. Fig. 454 shows one type of resistance box. Each coil has a different resistance, and a wide variation in resistance may be produced by removing different plugs or combinations of plugs. The wires used for resistance coils are often made of either manganin or constantan; these alloys have quite a high resistance, and their resistance is not much affected by temperature changes.

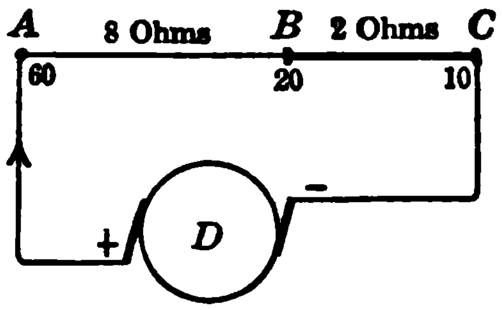



FIG. 451. — Fall of potential, resistance variable.

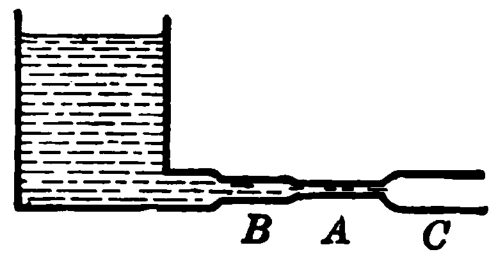



FIG. 452. — Water analogy. Resistance.

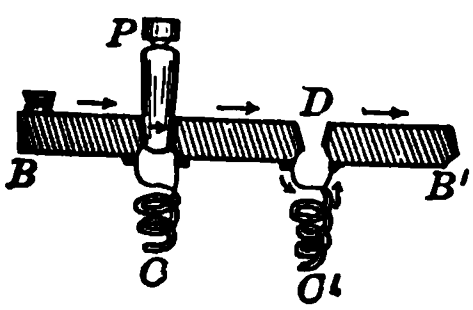



FIG. 453. — Resistance coils, showing winding.

Fig. 454. — Rheostat, showing coils.

**455. Shunt or Divided Circuit.** When conductors are connected in *series* the current flows through each of them in turn, so the *total* resistance is equal to the *sum* of the separate resistances. Very often, however, conductors are joined in parallel or multiple as shown in Fig. 455. Either branch of such a *divided* circuit is said to be a *shunt* to the other. Suppose we wish to find the total resistance $R$ of such a divided circuit. One branch $r$ has a resistance of 2 ohms, and the other branch $r'$ has a resistance of 3 ohms. The *conductance* of a wire may be defined as the reciprocal of its resistance. Therefore the total conductance equals $\frac{1}{R}$; the conductance of branch $r$ equals $\frac{1}{r}$; and the conductance of branch $r'$ equals $\frac{1}{r'}$. The total conductance equals the sum of all the separate conductances. Then

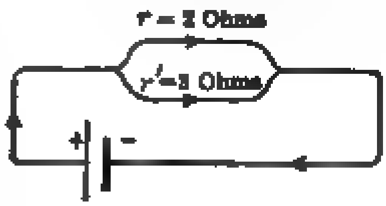


Fig. 455. — Shunt circuit.

$$\frac{1}{R}=\frac{1}{r}+\frac{1}{r'}.$$

Substituting the known values, we find that

$$\frac{1}{R}=\frac{1}{2}+\frac{1}{3}.$$

Whence $R=1.2$ ohms.

The fact that the total resistance of a shunt circuit is less than that of any branch usually astonishes the student.

It seems very reasonable, however, if we stop to consider that more water flows through two parallel pipes than through a single pipe. Suppose a large building is filled with people. It is emptied with greater readiness when the number of exits is increased. There is less resistance when some of the people use different doors than when the entire crowd uses one door only.

**456. Current in Shunt Circuit.** If there are two exits of equal width from a building, we would expect about the same number of people to pass out each exit. Just so, if the two conductors of a divided circuit have the same resistance, we would expect one half the current to flow through each branch. This is exactly what happens. If we have more than two conductors, all having the same resistance, then the amount of current flowing through each equals $\frac{1}{n}$ of the total current. Suppose in Fig. 455 the current in the main circuit is 5 amperes; then $\frac{3}{5}$ of the current, or 3 amperes, flows through the branch $r$ where the resistance is less, and $\frac{2}{5}$ of the current, or 2 amperes, flows through the branch $r'$. Just as more people can pass out through a *wide* door, so *more* current in a divided circuit flows through the branch having the *less* resistance. By the use of shunt circuits in electric wiring, it is possible to vary the strength of the current in different parts of the circuit.

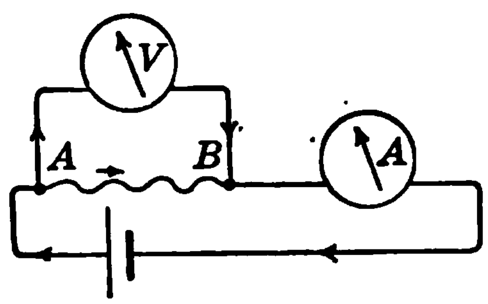



Fig. 456. — Voltmeter-ammeter method of finding resistance.

**457. Measurement of Resistance.** It is often necessary to measure the resistance of a conductor. Several methods are in common use:

*Voltmeter-ammeter method.* This is one of the simplest methods of measuring resistances. A voltmeter which is connected *in parallel* across the terminals of the conductor $AB$, Fig. 456, gives the potential difference between the

ends of the conductor. An ammeter *in series* shows the amount of current flowing through the circuit. By Ohm's law, the resistance $R$ equals $\frac{\text{P.D.}}{I}$. Why must the voltmeter be a *high-resistance* instrument and the ammeter an instrument whose resistance is practically zero? Why is a voltmeter always connected in parallel and an ammeter in series?

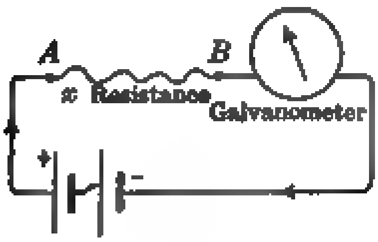


FIG. 457. — Finding resistance by substitution.

*Substitution method.* A few Daniell cells, grouped in series, are connected in series with a sensitive galvanometer and the conductor whose resistance is to be found. See Fig. 457. After the amount of deflection has been noted, a graduated rheostat is substituted for the conductor. The rheostat is then adjusted until the deflection of the galvanometer needle is the same as before. The conductor therefore has the same resistance as that shown by the rheostat.

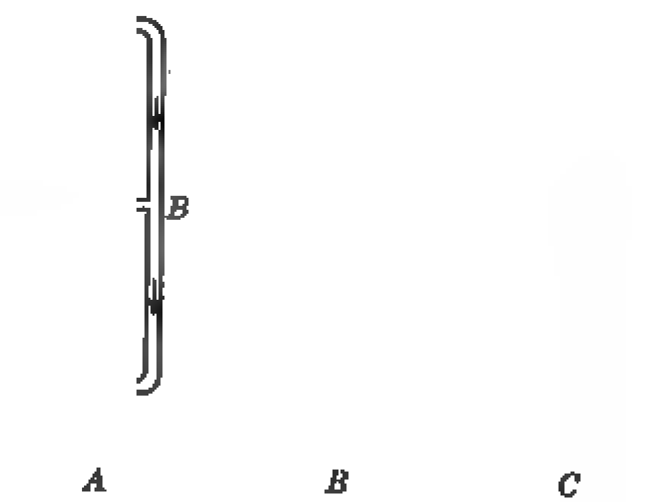


FIG. 458 — Wheatstone bridge. *A*. Water analogy. *B* Bridge, unbalanced. *C*. Balanced bridge.

*Wheatstone bridge method.* When water flows through two parallel pipes, the water meter $M$ will show no current flowing through the pipe $AB$, Fig. 458 $A$, provided both ends of the pipe are the same height. This fact is obvious, since the pressures at either end are equal. If the end $A$ is raised to point $C$, for example, the water then flows through $AB$ toward $B$. Conversely, raising the end $B$ reverses the flow.

The Wheatstone bridge is analogous in principle. If the electrical pressures at $A$ and $B$ of Fig. 458 $B$ are equal, no current flows through the galvanometer $G$. The unknown resistance is introduced at $X$ and graduated resistance boxes are introduced at $R$, $R'$, and $R''$, as in Fig. 458 $C$. These known resistances are then adjusted until the galvanometer shows no deflection in either direction. Then $R:X = R':R''$. Since $R$, $R'$, and $R''$ are all known quantities, the resistance of $X$ may be easily computed.

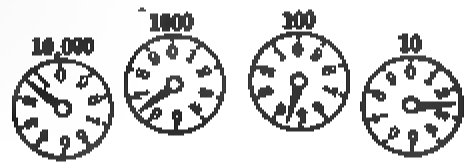



FIG. 459. — Kilowatt-hour meter dials.

One form of Wheatstone bridge uses a uniform wire instead of the resistance coils $R$ and $R'$. The galvanometer terminal is then slid along the wire until points $A$ and $B$ are of equal potential and no current flows through the galvanometer. In the equation given in the preceding paragraph, the length of one segment of wire is substituted for resistance $R$ and the length of the other segment is substituted for resistance $R'$.

FIG. 460. — Watt-hour meter, D.C. (Direct current).

**458. Electric Power.** We have learned that chemical energy is stored in storage cells. The *capacity* of such cells is generally expressed in ampere hours. For example, a

cell of 20 *ampere hours* can produce a current of 1 ampere for 20 hours or a current of 4 amperes for 5 hours. *Electrical energy* may be delivered at a slow rate or it may be delivered very rapidly. The rate at which *electrical energy* is delivered is called *electrical power*. *The unit of electrical power is the watt. The watt equals a current of one ampere driven by a pressure of one volt.* Hence, *volts* × *amperes* = *watts*. 1000 watts = 1 kilowatt. Electrical energy is usually sold by the *watt-hour*, or the *kilowatt-hour*. If the pressure is one volt, a current of one ampere flowing continuously for one hour uses one *watt-hour* of electrical energy. A flat-iron operating on a 110-volt circuit has a current of 5 amperes flowing through its coils continuously for one hour. It uses 550 watt-hours of electrical energy, or 0.55 kilowatt-hour. Electrical power may be measured by a voltmeter and ammeter. Suppose we connect a voltmeter across the terminals of an arc lamp and an ammeter in series with the lamp. The voltmeter gives the fall of potential across the arc lamp, and the ammeter in series gives the current flowing through the circuit. The product of the voltage times the amperage equals watts. Electric watt-hour meters are made to record their readings directly in kilowatt-hours. The right-hand dial reads by kilowatt-hours from 0 to 10; the next dial reads by 10's

FIG. 461. — Watt-hour meter, A C. (Alternating current).

from 0 to 100; the third dial reads by 100's to 1000; the fourth by 1000's, to 10,000. In Fig. 459 the meter reads 1642 kilowatt-hours. An employee of the company supplying the electrical energy reads the meter every month. The amount of energy used in kilowatt-hours equals the difference between the two readings. Figs. 460 and 461 show different types of watt-hour meters.

## SUMMARY

A galvanometer is used to detect the presence of an electric current, to determine its direction, or to measure its pressure and strength. A high-resistance galvanometer calibrated to read volts directly is a voltmeter. A low-resistance galvanometer calibrated to read amperes is an ammeter.

The fall of potential along a conductor is directly proportional to its resistance. An ammeter shows the same reading in one part of a series circuit as in another part.

The joint resistance of several conductors in series equals the sum of the several resistances. When conductors are joined in shunt, the reciprocal of the total resistance equals the sum of the reciprocals of the individual resistances.

By the use of a voltmeter and an ammeter, the resistance of a conductor may be found directly. (Ohm's law.) Resistance may be found by substitution or by the use of a Wheatstone bridge.

The watt is the unit of electrical power. Volts times amperes equals watts. One kilowatt equals 1000 watts. Power companies usually charge for electrical energy at a certain price per kilowatt-hour.

## QUESTIONS AND PROBLEMS

1. Voltmeters are connected in parallel, and ammeters in series in electrical circuits. Give the reason in each case.

2. Which is more apt to be injured by the heating effects of an electric current, a voltmeter or an ammeter? Explain.

3. Why is a low-resistance conduetor generally connected as a shunt across the terminals of an ammeter? Such an instrument is said to be "fool-proof." Explain.

4. Read your electric meter and record its reading. Read it again two weeks later and figure the cost of the electricity used during the two weeks' interval at the current price per kilowatt-hour.

5. New lamp bulbs usually have the power consumption in watts marked upon them. State clearly how you could use a few 40-watt lamps to check the accuracy of your meter.

6. Resistance coils of 5, 7, and 13 ohms respectively are joined in series with a cell whose E.M.F. is 2 volts. If the internal resistance of the cell is 0.2 ohm, what current flows through the circuit?

7. When 5 incandescent lamps are connected in series on a line whose total fall of potential is 550 volts, what is the difference of potential between the terminals of each lamp?

8. Five incandescent lamps are connected in parallel on a line whose total fall of potential is 110 volts. What is the fall of potential between the terminals of each lamp?

9. Suppose the resistances used in problem 6 are all joined in multiple. What current will flow in the main circuit? Make a diagram.

10. A storage cell, E.M.F. equals 2 volts and internal resistance 0.1 ohm, is connected to the terminals of two coils in parallel. If the resistance of one coil is 4 ohms and that of the other 5 ohms, what is their total resistance? What current flows in the main circuit? What current flows in each branch? (The student should always make a diagram before attempting to solve problems of this type.)

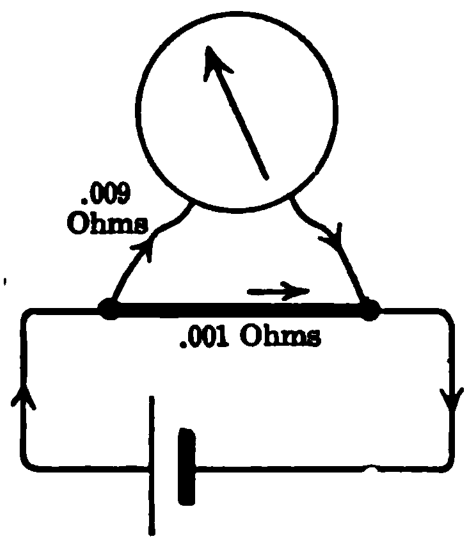


FIG. 462. — Shunt across ammeter.

11. Suppose an ammeter whose resistance is 0.009 ohm can safely carry 10 amperes. If it reads 10 amperes when connected in series, what will be its reading after a shunt of 0.001 ohm resistance has been connected across its terminals as in Fig. 462? How strong a current can then be safely used with the ammeter?

12. Lamps are rated commercially in watts. How many watts does a 16 C.P. carbon filament lamp use if its resistance is 220 ohms and the voltage between its terminals is 110? How many watts per candle does it use?

**13.** A tungsten lamp operating on a 110-volt circuit uses 0.363 ampere of current. How many watts does it use? Such a lamp gives about 32 candle power. How many watts does it use per candle power? Compare the result given by the carbon filament lamp of problem 12.

**14.** A flat-iron uses 4.5 amperes of current when operating on a 110-volt circuit. What is the cost of operating this flat-iron 4 hours at 10¢ per kilowatt-hour?

**15.** A man uses four 25-watt lamps an average of 2 hours daily; he uses eight 40-watt lamps an average of one hour daily; he uses a flat-iron like that of problem 14 a total of 16 hours per month. What is his total electric bill for a month of 30 days at the rate of 10¢ per kilowatt-hour?

## CHAPTER 26

# INDUCED CURRENTS

**459. Electro-magnetic Induction.** Since a current of electricity flowing through a conductor sets up a magnetic field about the conductor, it seems reasonable to expect that a magnetic field will exert some effect upon a conductor which is moving through it. We may show that this is true. Let us connect the terminals of a spool of insulated wire to a galvanometer, as in Fig. 463, and then thrust a bar magnet down into the spool. The galvanometer needle is deflected, showing that an *induced* current is set up in the spool of wire. When the bar magnet is withdrawn, a current is produced which flows through the coil in the opposite direction.

Fig. 463. — Magnet induces E.M.F.

Michael Faraday in 1831 was the first to show that *a current is induced in a conductor when a magnet is so moved that its lines of force are intersected by the conductor.* Since nearly all the electricity used commercially is now generated by induction, this discovery of electro-magnetic induction by Faraday is one of the most important discoveries ever made in the field of electricity.

**460. Induction Is Produced by a Conductor Moving through a Magnetic Field.** If we connect the ends of a coil of wire to a galvanometer and then thrust the coil down over

**Joseph Henry** (1797–1878) was an American physicist. He developed the electro-magnet. He transmitted current through about a mile of fine copper wire and caused the armature of a magnet to be attracted. Henry is the inventor of the telegraphic principle and of the relay. He was the first to observe the phenomenon of self-induction. As Secretary of the Smithsonian Institute he founded the Weather Bureau.

**Michael Faraday** (1791 1867) was a distinguished physicist and chemist. He was Assistant to Sir Humphry Davy at the Royal Institution. When the brilliant Davy was asked what he considered his greatest discovery, he is said to have replied, "Michael Faraday." Faraday liquefied certain gases. He discovered the laws of electrolysis. His researches in the field of induction led to the development of the dynamo and the magneto.

one of the poles of a horseshoe magnet, as shown in Fig. 464, the needle of the galvanometer is deflected; this shows that a current is induced in the moving coil as its wires cut the lines of force in passing through the magnetic field. *If the circuit is closed, a current is always induced in a conductor when it cuts magnetic lines of force.* It does not matter whether the magnet moves past the conductor, or the conductor moves through the field of force of the magnet. If we let a conductor or coil remain at rest in a magnetic field, no current is induced. *One or the other must be in motion to produce an induced current.* The more quickly the coil is thrust down over the magnet or withdrawn, the greater the induced current. Later it will be shown that induction may be produced in a conductor by varying the strength of a magnetic field surrounding it. The student must distinguish between *induced E.M.F.* and *induced current.* If the ends of the coil used in Fig. 464 are not connected, and the coil is on open circuit, an induced E.M.F. is set up when the coil moves through the magnetic field, but no current can flow. An induced E.M.F. has potential energy; when the circuit is closed, its energy becomes kinetic, and an induced current flows through the circuit.

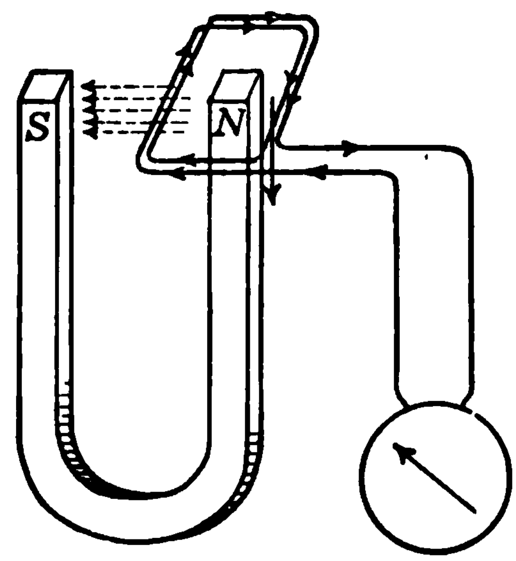


FIG. 464. — Electro-magnetic induction.

**461. Lenz's Law.** As the coil of Fig. 464 moves down over the north pole of the magnet, an induced current flows in such direction that an N-pole is produced in the face of the helix approaching the north pole of the magnet. The magnetic field, produced by the current which is induced, opposes the permanent field of the magnet by repulsion between the two like poles. When the magnet is being withdrawn, the induced current is reversed; an S-pole is

produced by induction in the face of the helix which is adjacent to the magnet, and the motion is opposed, this time by attraction between the unlike poles. If we repeat the experiments by thrusting the coil down over the S-pole of the horseshoe magnet, an S-pole is now induced in the adjacent face of the helix as it approaches the magnet, and an N-pole is set up as the coil recedes. The results of these observations may be summarized in the statement of Lenz's law: *An induced current set up in a conductor always flows in such a direction that the magnetic field which it produces opposes the motion of the conductor or the field magnet.* From the law of the conservation of energy, this is exactly what we might expect. If the reverse were true, then perpetual motion would be possible.

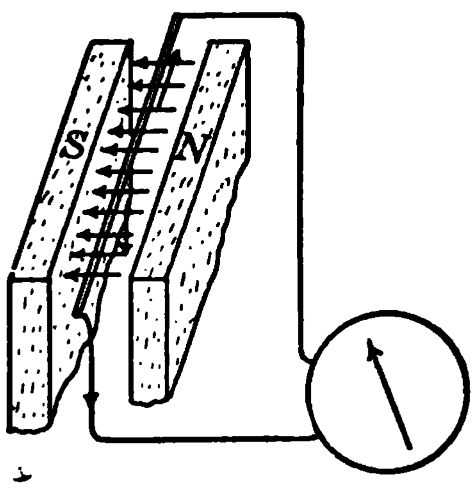



FIG. 465. — Conductor cuts lines of force.

**462. Direction of Induced Current.** When a wire is shoved down between the poles of a horseshoe magnet, as shown in Fig. 465, an induced E.M.F. is set up in the wire. If we close the circuit, an induced current flows. By connecting the ends of the wire to a sensitive galvanometer, it may be shown that the current flows in one direction as the wire moves *down* between the poles of the magnet, and in the reverse direction as it moves *up* through the magnetic field between the two poles. Cutting lines of force in one direction sets up a current in a conductor; when the conductor cuts lines of force in the opposite direction, the current is reversed. When the conductor moves parallel to the lines of force, no current is induced.

The direction in which the induced current flows may be found by the use of the following right-hand rule, which is sometimes called the *dynamo rule: Let the extended forefinger of the right hand point in the direction of the lines of*

*force; turn the hand so the extended thumb points in the direction the conductor is moving; the middle finger bent at right angles to both the thumb and fore-finger will then point in the direction of the induced current.* Applying this rule to Fig. 465 we find that the current flows toward the observer as the wire moves up between the poles of the magnet; it flows from him as the wire moves down between the poles of the magnet.

**463. Strength of the Induced E.M.F.** We have already seen that a higher E.M.F. is induced when a conductor moves rapidly through a magnetic field. If a stronger magnet is used, the strength of the E.M.F. is further increased. Using more loops in the coil also increases the E.M.F. *The strength of an induced E.M.F. depends upon the number of lines of force cut per second.* To produce an E.M.F. of one volt, 100,000,000 lines of force must be cut per second.

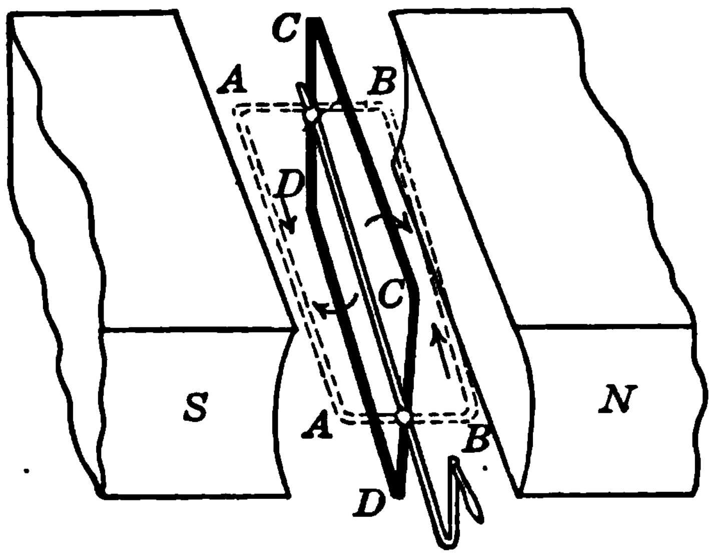


FIG. 466. — Simple ideal dynamo.

*In order to build up a high voltage by induction, we may increase the strength of the field magnet, increase the speed,* or *increase the number of turns in the coil.*

**464. Induced Current in a Revolving Loop.** Let us replace the single wire used in Fig. 465 with a loop of wire mounted on an axis, as in Fig. 466. Such an arrangement is a simple ideal dynamo. The loop of wire serves as the armature, and the horseshoe magnet as the field magnet. When the crank is turned, one wire of the loop moves down past the north pole of the field magnet as the other moves up past the south pole. By applying the right-hand rule we find that the current encircles the loop in one direction during one half-revolution, and in the opposite direction during the

other half-revolution. A current that flows in one direction during part of a cycle and then in the opposite direction during the rest of the cycle is called an *alternating* current. The E.M.F. rises to a maximum in one direction and then falls to zero; it then rises to a maximum in the other direction and again falls to zero. The curve of Fig. 467 represents the E.M.F. of such a rotating loop during one complete *cycle*. The E.M.F. reaches its maximum when both wires of the loop are cutting a maximum number of lines of force as at $AB$; when the loop reaches the position $CD$, both conductors are moving parallel to the lines of force, and the E.M.F. falls to zero.

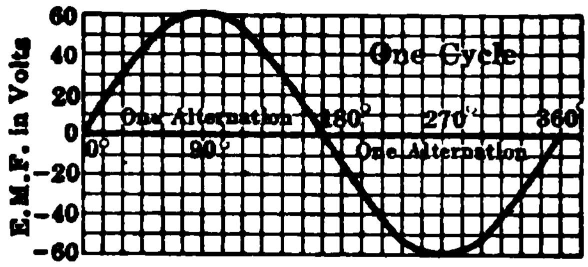



Fig. 467. — Alternating E.M.F. curve.

**465. How Current Is Taken from the Armature.** If we were to connect the ends of a revolving loop direct to some instrument, the wires would be twisted off after a few revolutions of the loop. To utilize the current for work in an external circuit, the ends of the loop are soldered to two brass rings, called *slip-rings*, which are mounted on the same shaft as the loop. These rings are carefully insulated from each other so the current will not short-circuit through the loop. Two metal strips or carbon blocks, called *brushes*, rest lightly on the slip-rings as they revolve with the loop. The ends of the wires used in the external circuit are connected to the brushes, which take current from the slip-rings and transmit it to the external circuit. See Fig. 468.

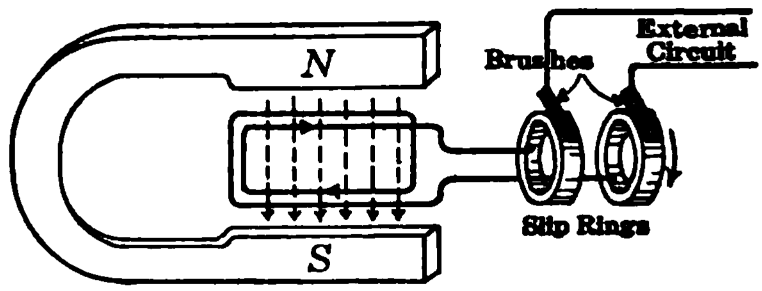



Fig. 468. — Slip rings.

**466. The Magneto.** Since 100,000,000 lines of force must be cut per second to give an E.M.F. of one volt, the single loop of Fig. 466 furnishes too feeble a voltage to be of

any practical value. In commercial machines the *armature* consists of a *large* number of loops or coils wound on an iron core. The simple H-armature devised by Siemens consists of a grooved iron cylinder wound with a large number of loops of insulated wire. See Fig. 469. By rotating such an armature rapidly between the poles of a strong magnet, a high E.M.F. can be obtained. In the *magneto* several permanent horseshoe magnets are used as *field magnets.* The magneto generates an alternating current which is used extensively for ringing telephone bells and with a spark-coil for ignition in gas engines.

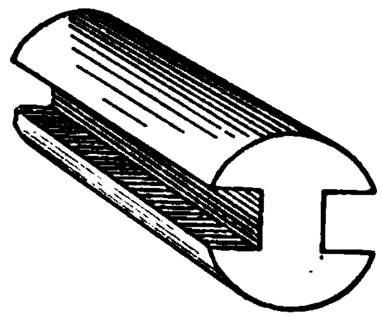


FIG. 469. — Siemens H-armature.

**467. The Alternating-current Dynamo.** *The dynamo is a machine for transforming mechanical energy into electrical energy.* The simple alternating-current dynamo differs from the magneto in only one important respect: the field magnet consists of a very strong *electro-magnet.* Dynamos consist of three essential parts: (1) The *field magnet,* which produces lines of force; (2) the *armature,* which consists of an iron core wound with a large number of coils of insulated wire; the armature revolves on an axis between the poles of the field magnet, and in so doing cuts magnetic lines of force; (3) the *slip-rings* and *brushes.* All dynamos generate *alternating* current in the armature exactly as in the case of the single rotating loop. When this current is taken from the armature by the brushes which rest on the slip-rings the current in the external circuit is also *alternating;* that is, it flows through the external circuit first in one direction, and then in the opposite direction. Since there are two alternations for each revolution or cycle of the armature, and most commercial machines have a frequency of 60 cycles per second, the number of alternations is 120 per second. For use in heating, lighting, and certain power purposes the alternating current is satisfactory; hence *alternators*

are extensively used. For electro-plating or for charging storage batteries, the alternating current cannot be used; it must be changed or transformed into a current that is *uni-directional.*

**468. The Direct-current Dynamo.** In only one particular does the *direct-current* dynamo differ from the alternator. The terminals of the armature are not connected to slip-rings, but to the segments of a commutator. The *commutator* (*commute,* to change) changes the alternating current of the armature into a current which flows in one direction *only* in the *external* circuit. Such a current is called a *direct* current, a *continuous* current, or even better, a *uni-directional* current, to distinguish it from the *alternating* current. In its simplest form the commutator consists of a ring of brass which has been split into two semicircular segments, carefully insulated from each other. The terminals of the armature coil are soldered one to each segment, as shown in Fig. 470. Brushes resting on these segments take current from them just as they do from the slip-rings of the alternator.

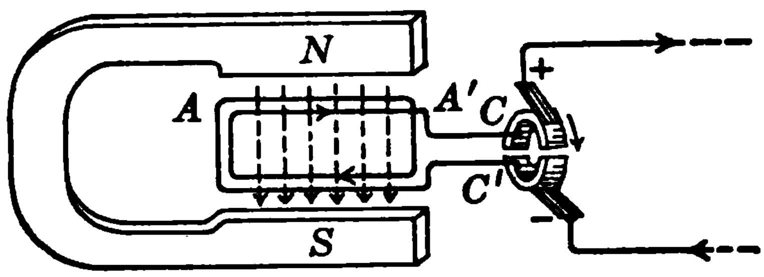


FIG. 470. — Commutator.

As the coil of Fig. 470 rotates so that the top wires $AA'$ move toward the observer, the current flows to the commutator segment $C$. The brush bearing on this segment is receiving current, hence it is positive. As the armature rotates, the wires $AA'$ of the loop begin to cut lines of force in an opposite direction as in passing the S-pole they move from the observer. The current then reverses and flows to segment $C'$. During this rotation of the coil or loop the segment $C'$ has also moved until it is now in contact with the positive brush. Therefore the brush marked plus always rests on the segment to which the current from the armature is flow-

ing. Thus the current is alternating in the armature, but uni-directional in the external circuit. The brushes are so adjusted that the commutator segments change from one brush to the other at the same time the current reverses in the armature. When only one coil is used in the armature, the E.M.F. is pulsating, as shown in the curve of Fig. 471.

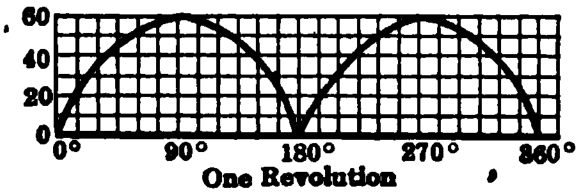



FIG. 471. — Direct E.M.F. curve.

To secure a more constant voltage a large number of coils are used in the commercial dynamo; they are set at angles to one another, so that some coil is always cutting lines of force.

**469. Armature Types.** The *drum-wound* and the *ring-wound* armatures are two types that are in common use.

The core of a drum-wound armature is built up of a large number of iron discs, Fig. 472, so mounted on their axes that grooves are formed in which the insulated wires are wound. To prevent *eddy* currents being set up in the iron core by induction, these discs are insulated from each other. Eddy currents heat the core and cause a waste of energy. A large number of coils are used, each coil requiring two commutator segments. Fig. 473 shows a drum-wound armature of the commercial type.

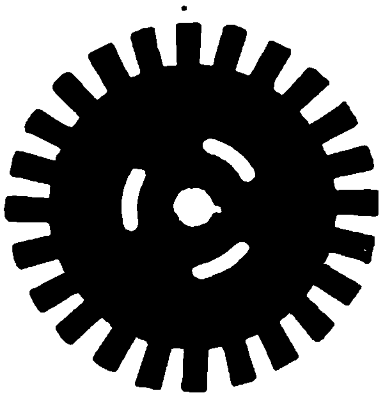


FIG. 472. — Slotted disc, for armature.

In the ring-wound armature the insulated wire is wound in the form of a spiral on an iron ring or shell in the manner shown in Fig. 474. The wires on the inside and at the ends do not cut lines of force, since the lines of force follow the line of least resistance through the iron itself, as shown by the dotted lines in the figure. With the drum-wound type all the wires except those at the ends of the drum cut lines of force. Therefore the ring winding

Fig. 473. — Drum armature. An end of each loop is connected to a commutator segment.

requires more wire to produce a given voltage, unless the diameter of the armature becomes so great that much wire is wasted at the ends. On the other hand, it is easier to insulate the winding of the ring type and more convenient to

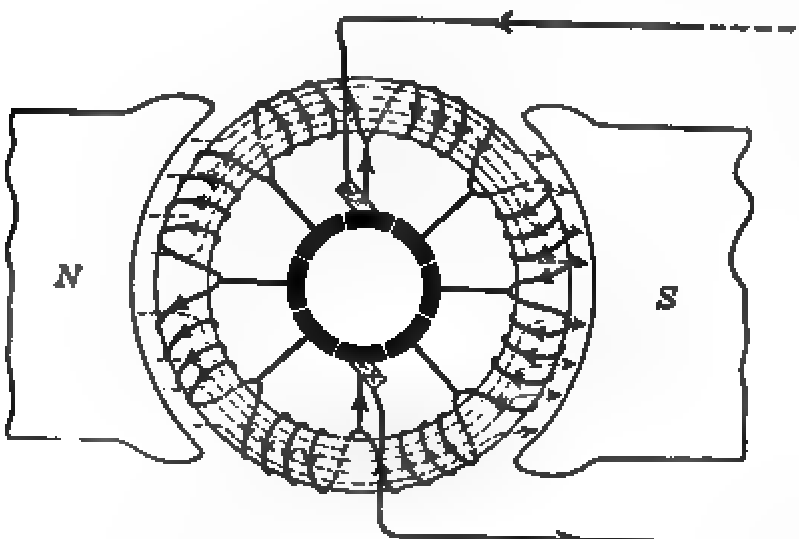



Fig. 474. — Ring-wound armature.

make repairs. It is often used for very high voltage work, such as arc lighting, or for power transmission.

**470. How the Field Magnet Is Magnetized.** Some current must be available to magnetize the field magnets of a dynamo. Sometimes the field is magnetized by passing through its winding the current from a number of storage cells. See Fig. 475. For alternators a small direct-current dynamo, called an *exciter*, is more often used. Since the current through the field is a very constant one, the voltage of the alternator does not vary if its speed is uniform. The direct-current dynamo is usually a *self-exciting* machine; a part or all of the current from the armature of the dynamo itself flows through the magnetic field.

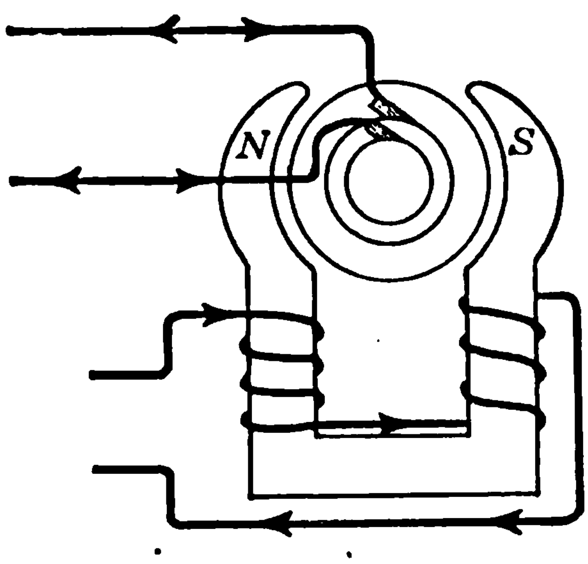


FIG. 475. — The field of an alternator is magnetized by storage cells or by a small D.C. dynamo.

**471. Self-exciting Machines.** Self-exciting dynamos may be of three different types: (1) *Series-wound;* (2) *shunt-wound;* (3) *compound-wound.* A little residual magnetism is always left in the field magnets of a dynamo. Then as the armature begins to rotate, the few lines of force are cut and enough voltage is built up to cause an induced current in the armature. The current from the armature is then used to increase further the strength of the magnetic field.

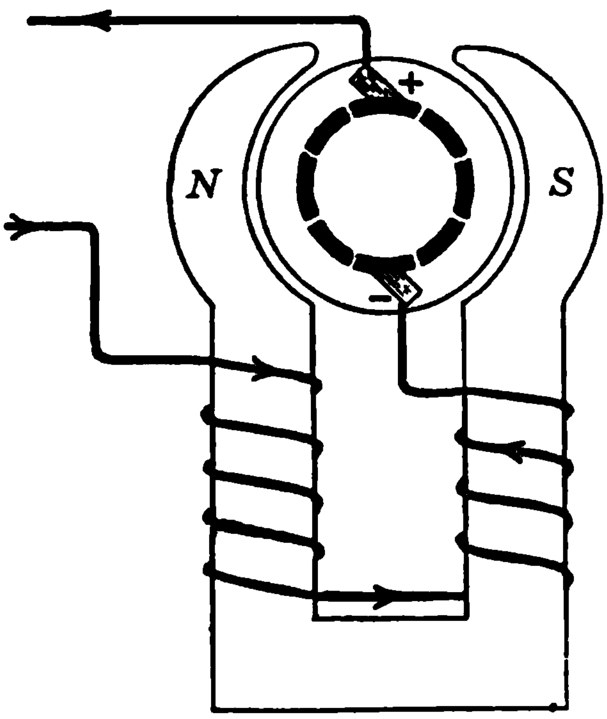


FIG. 476. — Series-wound dynamo.

In a *series-wound* dynamo the wires of the external circuit are

wound around the poles of the field magnet. See Fig. 476. If the resistance of the external circuit is increased, less current flows through the circuit and the magnetic field decreases in strength. Fewer lines of force are cut per second and the voltage drops. Such a dynamo may be used when the external resistance is nearly constant, or if storage batteries are used with it to help energize the field. It is suitable for use with arc lamps, when all the lamps are turned on at one time.

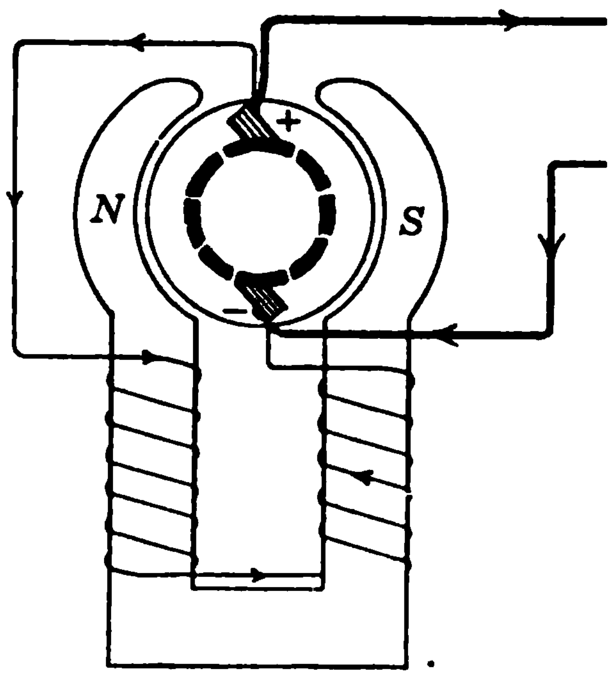



FIG. 477. — Shunt-wound dynamo.

In a *shunt-wound* dynamo the current from the armature divides, a part flowing directly to the external circuit, and a smaller part flowing through a shunt which is wound about the field magnet. The shunt circuit consists of a large number of turns of smaller wire. As the resistance in the external circuit increases, more current flows through the shunt and the magnetic field is strengthened. The voltage of a shunt-wound dynamo rises as the external resistance increases. See Fig. 477.

The *compound-wound* dynamo combines the merits of the series- and shunt-wound dynamos. See Fig. 478. The few coils in series tend to lower the voltage as the external resistance increases, but this tendency is neutralized by the shunt winding, which tends to increase the volt-

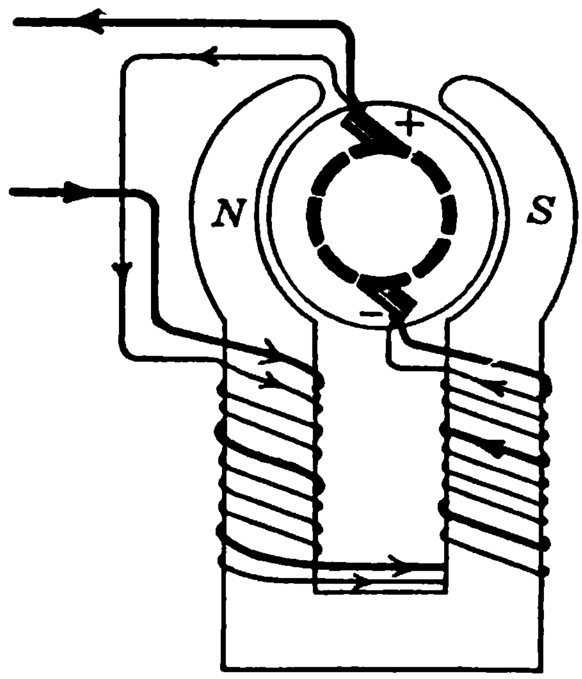



FIG. 478. — Compound-wound dynamo.

FIG. 479. — Eight-pole field, for D.C. dynamo.

age as the external resistance increases. When the two windings are properly adjusted, a compound-wound dynamo gives quite a constant voltage, even under varying load.

**472. Alternators and Direct-current Dynamos Compared.** A direct current may be used for practically any purpose. Fig. 479 shows an eight-pole field for a commercial direct-current dynamo. The drum armature of Fig. 473 is shown in the field in Fig. 480. We have learned that the alternating current cannot be used for electro-plating, electro-metallurgy, and charging storage batteries. It is not so desirable

FIG. 480. — Eight-pole direct-current dynamo.

for arc lighting. The alternations are so rapid that it is suitable for use with incandescent lights. If we bear in mind that the duration of vision is never less than $\frac{1}{10}$ of a second, and that the alternations occur at intervals of $\frac{1}{120}$ of a second, we can understand why there is no flickering in an incandescent lamp. For lighting purposes a frequency of 60 cycles per second is generally used. In the two-pole machine there are two alternations and one cycle per revolution. For a frequency of 60 cycles, the armature of a bi-polar machine must make 3600 revolutions per minute. To per-

FIG. 481. — Rotor and stator of a commercial alternator.

mit a reduction in speed, more poles are sometimes used; a four-pole machine has two cycles and four alternations per revolution; an eight-pole machine has four cycles and eight alternations per revolution. To produce 120 alternations per second, an eight-pole machine must make 900 revolutions per minute. For power transmission a frequency as low as 25 cycles per second is commonly used.

The alternator has certain advantages over the direct-current dynamo. It is easy, to raise or lower the voltage of an alternating current without introducing resistance.

Therefore a variation in the voltage is possible at different points in the same circuit.

A direct-current dynamo is not suitable for very high voltages, since it becomes increasingly difficult to insulate the commutator segments as the voltage rises. In very high voltage alternators the armature is stationary, and the field magnet rotates inside the armature. Such a stationary armature is called a *stator*. The rotating field is called the *rotor*. The current can be taken directly from the stationary armature without the use of slip-rings and brushes. See Fig. 481.

**473. The Electric Motor.** *The electric motor transforms electrical energy into mechanical energy.* It does not differ in construction from the direct-current dynamo. Current from a dynamo or other source is led into an electric motor; there it produces two magnetic fields, one in the armature and the other in the field magnet. These two fields attract and repel one another with sufficient force to cause the armature to rotate rapidly. The power from the motor is transmitted to various machines by a belt wheel attached to the rotating armature, or directly by means of gear wheels.

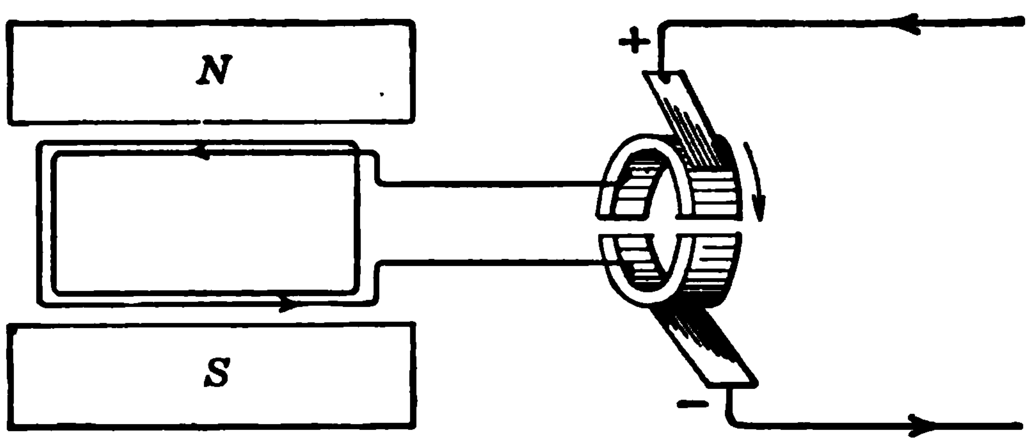


FIG. 482. — Motor diagram.

By the use of Fig. 482, we may explain in detail why the armature of a motor rotates. As the current flows through the armature loop in a counterclockwise direction, the loop becomes a magnet with its N-pole toward the observer, and its S-pole from him. The north pole of the field magnet repels the N-pole of the loop and attracts its S-pole. The

south pole of the field magnet at the same time attracts the N-pole of the loop and repels the S-pole. These forces of attraction and repulsion all work together to turn the armature in the direction shown by the dotted arrow. If the current continued to flow in the same direction, the rotation of the armature would stop as soon as the N-pole reached a position adjacent to the south pole of the field. But when this point is reached, the commutator reverses the

FIG. 483. — Magnetic field of street car motor.

direction of the current which enters the armature, its polarity is reversed, and mutual attraction and repulsion occur as before. Inertia carries the poles past the points of dead center.

The direction of rotation may be found by the use of the *left-hand rule,* or *motor rule.* Extend the fore-finger of the *left* hand in the direction of the lines of force; turn the middle finger, bent at right angles to both the thumb and fore-finger, so it points in the direction of current flow; the extended thumb then points in the direction of rotation.

The *torque*, or tendency to produce rotation, of a motor armature depends upon the strength of the current and upon the winding of the field and armature; since the strength of an electro-magnet depends upon the number of ampere-turns, the torque or twisting force of the armature depends

FIG. 484. — Armature for D.C. street car motor

upon the mutual attraction and repulsion of the field magnet and the armature.

**474. Series and Shunt Motors.** Direct-current motors may be shunt-wound or series-wound. *Shunt motors* are extensively used in machine shops since their speed is not much affected by varying loads. Fig. 483 shows the magnetic field of a street car motor. The armature is shown in Fig. 484. *Series motors* are used on automobiles and street cars. The torque of a series motor is much greater at starting than that of a shunt motor. Hence the series motor is used when a motor must start under load. In street car motors the armature is connected with the load by means of gear-wheels, which at the same time reduce the speed.

A series motor is the only type that will run on either direct or alternating current. Hence it is used extensively in small motors for turning fans, vacuum cleaners, sewing machines, etc. The current reverses in the field at the same time as in the armature; hence such a motor will run on alternating current. Street cars are generally operated at a voltage of 550. The current is supplied to the motor from a trolley wire or a third rail. The current flows through the car-wheels to the track, which forms the return circuit, Fig. 485.

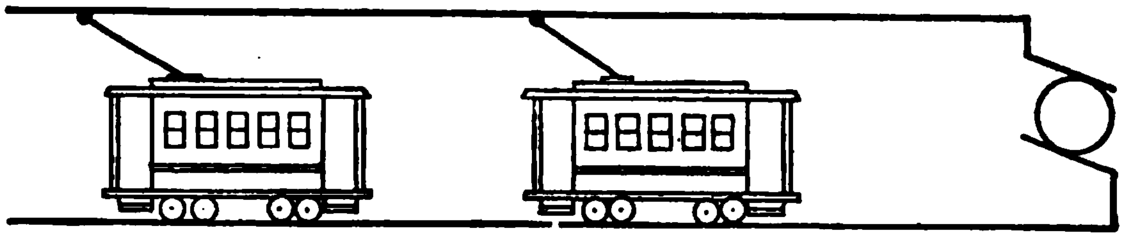


FIG. 485. — Street cars are operated in parallel.

**475. Alternating-current Motors.** Of the several types of alternating-current motors that are in use, only one type will be discussed. The *induction* motor consists of two parts; the *stator,* which differs little from the stator of an alternator in the manner in which it is wound; and the *rotor,* which is built of copper bars laid in slotted, laminated iron cores. In the type known as the *squirrel-cage rotor* the copper bars are all connected at each end to copper rings, Fig. 486. When an alternating current passes through the windings of the stator, a rotating magnetic field is set up. The rotor is not connected in any way to the stator or the electrical supply, but the rotating magnetic field produces a current in the rotor by induction. The magnetic field set up in the rotor by this induced current is dragged after the rotating magnetic field in the stator. Thus the rotor turns very rapidly on its axis. Induction motors are made in all sizes; their advantage lies in their simplicity.

**476. Back E.M.F. Developed by a Motor.** Since the armature of a motor rotates in a magnetic field, it cuts lines

FIG. 486. — Squirrel-cage induction motor. The lower view shows the stator base; the upper view shows the rotor.

of force. This sets up an E.M.F., which opposes the motion of the armature (Lenz's law). Since the E.M.F. opposes the voltage operating the motor, it is called a *back E.M.F.* It acts practically the same as if resistance were introduced without producing its heating effects. In reality it makes the operation of the motor more economical. Suppose a motor operating on a 550-volt circuit develops a back E.M.F. of 500 volts. If its armature resistance is 5 ohms, then only 10 amperes of current will flow through the armature.

$$\frac{550-500}{5}=10 \text{ amperes.}$$

The current consumption is 500 watts. If the speed of the armature were reduced until the back E.M.F. falls to 400 volts,

then 30 amperes of current would flow through the armature and the current consumption would rise to 4500 watts.

**477. Starting Motors.** When a motor armature is at rest it develops no back E.M.F. The resistance of a motor armature is very low, hence the armature is liable to be "burnt out" if the full current is turned on before the motor is brought up to speed. Rheostats connected in series with the armature are used in starting motors, and the resistance is then gradually cut out as the speed of the motor increases. As the motor comes up to speed, resistance is gradually cut out of a *series* motor by moving the lever *L* to the right. Fig. 487. In starting a *shunt* motor the resistance in the field is increased as the resistance in series with the armature is cut out. Both of these operations increase the current flowing through the armature, and thus increase the speed of the motor. See Fig. 488. If an overload decreases the speed of a motor suddenly, an automatic circuit breaker opens the circuit and prevents injury to motor. Fig. 489.

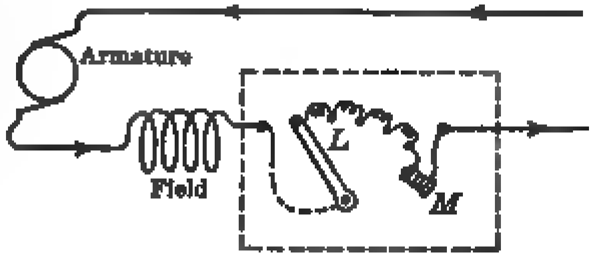


FIG. 487. — Starting box, series motor.

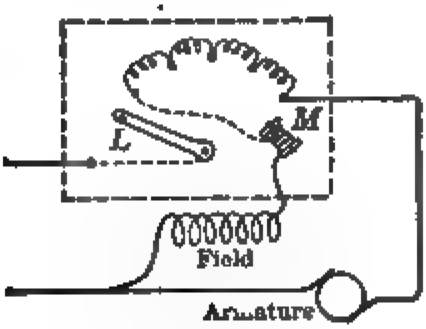


FIG. 488. — Starting box, shunt motor.

*Circuit breakers* are of two types; *overload* and *underload.* In the overload circuit breaker of Fig. 490, the current

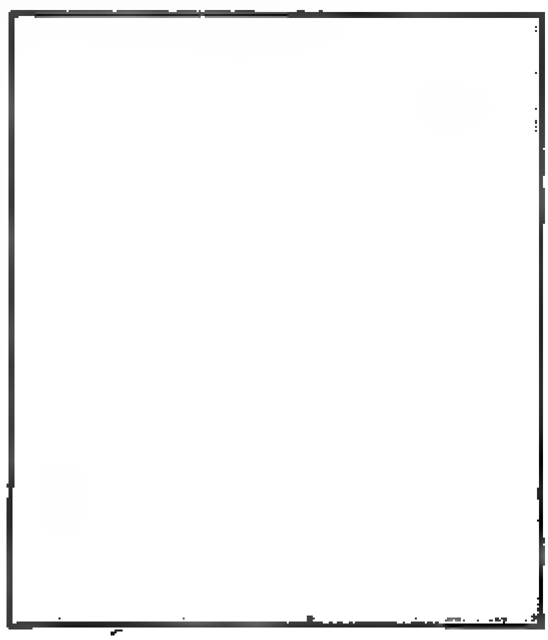


FIG. 489.—Automatic circuit breaker.

enters through stud $P$ and flows through the strap windings $C$ into the arm $D$; thence it flows through the contact plate $E$ into the stationary brush $F$, which is connected with the stud $Q$. The square core $A$ is magnetized to a degree which depends upon the current strength. When an overload occurs, the core becomes so strongly magnetized that the

FIG. 490. — Circuit breaker diagram.

end $K$ of the pivoted armature is lifted enough to release the handle. The resiliency of the coil $C$ then throws the arm outward and breaks the circuit, first through the brush fingers $F$ and the contact plate, and finally between the carbon blocks $F$ and $S$. The breaker is reset by pulling the handle down, thus bringing the roller $H$ into engagement with roller $G$ and forcing the arm back into its initial position.

The underload circuit breaker is especially useful when storage batteries are being charged. If the voltage of the dynamo that is being used to charge the batteries should be momentarily lowered below that of the batteries themselves, a current would flow back through the dynamo and cause

it to run as a motor. An underload circuit breaker may be set to break the circuit automatically if the voltage falls below a predetermined value.

## SUMMARY

An induced E.M.F. is produced in a conductor when it cuts lines of force. The induced current set up in a closed conductor cutting lines of force opposes the motion of the conductor through a magnetic field. Its strength depends upon the number of lines of force cut per second. An induced E.M.F. of one volt is produced when 100,000,000 lines of force are cut per second.

The dynamo transforms mechanical energy into electrical energy. The current in the armature alternates twice during each revolution. By means of a commutator, the alternating current may be converted into a uni-directional current in the external circuit.

The armature of a dynamo may be ring-wound or drum-wound. The field magnets may be excited by means of an independent current or the machine may be self-exciting. A self-exciting machine is series-wound, shunt-wound, or compound-wound.

The electric motor transforms electrical energy into mechanical energy. Since it cuts lines of force it also produces an induced E.M.F., which opposes the E.M.F. from the line wire.

## QUESTIONS AND PROBLEMS

1. Why is it impossible to charge a storage battery by using an alternating current?

2. A ship having an iron mast sails east. A wire running along the mast is connected at the top and bottom so that it makes a loop with the mast. Is an induced current set up in the wire? Is an induced E.M.F. produced? Does it matter whether the plane of the loop is coincident with or perpendicular to the earth's magnetic field?

3. Do you think there would be an induced current set up by a loop of wire revolving on a vertical axis in the earth's magnetic field? Explain.

4. What advantage has the dynamo over the magneto?

5. A motor operating on a 110-volt circuit develops a back E.M.F.

of 90 volts. The resistance of its armature and field is 4 ohms. What will it cost at 10¢ per kilowatt-hour to run this motor for 10 hours?

6. A few years ago one of the scientific papers received this query. "I have a $\frac{1}{2}$ H.P. hand dynamo. It turns very easily until I connect the dynamo with my motor; then it turns hard. What is the matter with my dynamo?" What answer would you make to this query?

*Suggested Topic.* Three-phase Currents.

## CHAPTER 27

# ELECTRO-MAGNETIC INDUCTION

**478. Varying the Strength of a Magnetic Field Induces a Current.** Let us connect the terminals of a coil consisting of many turns of fine insulated wire to a galvanometer. Then let us place a small coil wound with a few turns of coarse wire within the large one, and connect the small coil in circuit with a dry cell and contact key, as shown in Fig. 491. When the contact key is pressed, the galvanometer shows that a current is induced in the outer, or *secondary*, coil. If the key is held firmly, the induced current soon ceases to flow; when the circuit is broken, however, a current is induced in the opposite direction. As the key is pressed, the battery current sets up a magnetic field about the inner coil, which is called the *primary* coil. The lines of force then cut across the wires of the secondary coil, inducing in them an E.M.F., or if the circuit is closed, producing an induced current. While the current flowing through the primary is constant, the strength of the magnetic field does not vary, and no current is induced in the secondary. When the primary circuit is broken, the magnetic field decreases in strength, and thus induces an opposite E.M.F. in the secondary. *Increasing or decreasing the number of lines of force in a magnetic field induces an E.M.F. in a conductor present in that field.*

FIG. 491. — Varying field induces E.M.F.

**479. The Induction Coil.** Let us substitute for the contact key used in the preceding experiment a vibrator or automatic interrupter; then we have the essentials of an *induction coil* or *spark coil*. The coil shown in Fig. 492 uses a vibrator essentially the same as in the case of the electric bell. The current flows from the positive plate of the voltaic cell *B* through the primary coil and returns to the negative plate of the cell through the vibrator *V* and the post *P*. The primary coil consists of a few turns of coarse insulated wire wound on a bundle of iron wires, insulated from each other to prevent eddy currents.


FIG. 492. — Induction coil.

The secondary coil consists of many thousands of turns of insulated wire wound on a spool which surrounds the primary. Sometimes miles of fine wire are used on the secondary coil.

The current flowing through the primary magnetizes it, thus attracting the armature *A* and breaking the circuit at *D*. As the magnetic field in the primary decreases rapidly, an induced E.M.F. of high pressure is set up in the secondary. The core loses its magnetism, the spring of the vibrator closes the circuit, and an induced E.M.F. is set up in the opposite direction as the magnetic flux in the primary rises to a maximum. Therefore an intermittent E.M.F. is induced in the secondary coil as the circuit in the primary is alternately "made" and "broken."

The value of the E.M.F. produced in the secondary depends: (1) upon the rate at which the magnetic field varies; (2) upon the strength of the current in the primary;

and (3) upon the number of turns in the secondary as compared to the number of turns in the primary. Since the "break" of the current is much more sudden than the "make," the induced E.M.F. is usually about 10,000 times as high when the "break" occurs.

Though not essential, a condenser *C* is often used with an induction coil. It is connected as in Fig. 492, so the "break" comes between its terminals. The inertia of the current gives it a tendency to follow the armature and leap across the air-gap at *D* as the "break" occurs. When a condenser is used, this energy surges into the condenser; the "break" becomes much more sudden and the induced E.M.F. is increased. The spark at *E* is thus made thicker and longer. The condenser, immediately after the current is broken, discharges back through the primary coil. Thus it helps to demagnetize the core *M*.

**480. Uses of the Induction Coil.** The induction coil is used extensively to produce the jump-spark for ignition in gas engines. It is used to some extent in the so-called *medical* batteries. Very large induction coils are now made for use in *wireless telegraphy* and for *X-ray tubes*.

**481. Self-induction.** Let us connect two dry cells in series and then join one of the terminals to a piece of wire gauze; when the other terminal is drawn along the wire gauze a few feeble sparks are produced. If we repeat the experiment after an electro-magnet has been connected in series in the circuit, the sparks that are emitted are much longer and thicker than before. Just as one coil may produce mutual induction in a coil surrounding it, so one turn in a coil may produce induction in an adjacent turn of the same coil. The phenomenon is known as *self-induction*. In mechanics we learned that a body at rest tends to remain at rest and a body in motion tends to remain in motion. Self-induction is closely akin to inertia, since it opposes the flow of a current through

a coil, and also opposes the "dying out" of a current when the circuit is broken. The self-induced current is sometimes called the *extra current*. This *extra* current added to the *inducing* current causes the spark to be "fattened" when the circuit is "broken" as in the foregoing experiment.

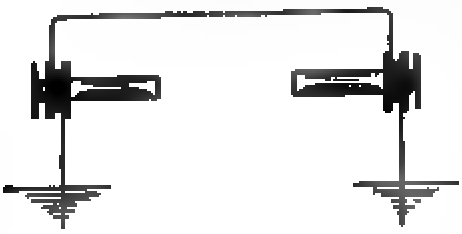


Fig. 493. — Simple telephone.

A *spark coil* consists of a large number of turns of insulated copper wire wound on an iron core. When such a coil is connected with two or three dry cells in series, quite a large spark is produced when the circuit is broken. Such a coil may be used for lighting gas jets or for ignition purposes.

**482. The Telephone.** The simple telephone is what is now known as the telephone receiver. It consists of a coil of fine insulated wire wound around one end of a permanent magnet. An iron disc near the end of the magnet is thrown into vibration by the sound waves. As this disc vibrates it changes the direction of the lines of magnetic force, since it offers a better path for lines of force than the air does. When two such instruments are connected as in Fig. 493, the vibrating disc induces a current in the coil around the magnet. This induced current produces a corresponding variation in the magnetic field of the telephone at the other end of the line, and causes its disc to reproduce the same vibrations.

Fig. 494. — Telephone transmitter.

**483. The Transmitter.** Since the telephone as described in the preceding paragraph is not suitable for distances beyond a few miles, the modern telephone uses a transmitter

which is much more sensitive. It consists of a small box *B*, Fig. 494, filled with particles of granular carbon. The back of the box is a fixed carbon plate attached to one terminal of a battery in series with the primary of a small induction coil. The front of the box is a plate attached to the vibrating diaphragm, which is connected with the other terminal of the induction coil primary. The sides of the box are made of insulating material. When a sound wave condensation presses the carbon particles closer together their resistance becomes less, and more current flows through the primary

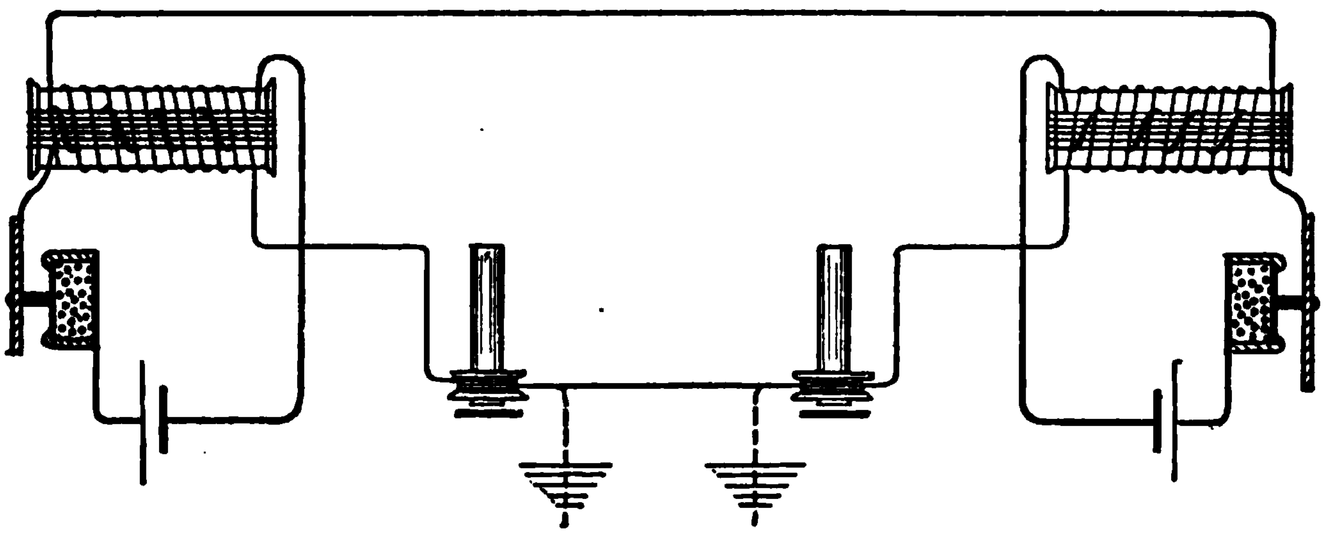


FIG. 495. — Local telephone system.

coil. This induces a higher voltage current in the secondary. Since the receivers are connected in series with the line wire and the secondary coil, the disc of the receiver is more strongly attracted. When a rarefaction occurs, the pressure on the carbon particles becomes less and a smaller current flows through the primary coil. The variation in the resistance of the carbon particles varies the strength of the primary current and at the same time produces *corresponding* variations in the induced current in the secondary. Thus the receiver disc reproduces the same vibrations as those impressed upon the disc of the transmitter. Fig. 495 shows a local-battery telephone system. Sometimes only one wire is used, the other being grounded as shown by the dotted lines. In the vicinity of trolley lines or electric lighting

circuits two wires must be used to prevent induction from stray earth currents. The use of two wires largely eliminates confusing noises from cross-circuits. Fig. 496 shows

FIG. 496. — Telephone cable, $2\frac{5}{8}$ in. in diameter. This cable contains 1200 pairs of No. 24 B. & S. gauge copper wire, insulated with strips of paper.

a section of lead cable used for laying telephone wires in conduits. A few years ago the anchor of a vessel in New York harbor dragged a cable of this type. Try to imagine the difficulty involved in untangling such a network of wires.

**484. The Voltage Transformer.** If we connect the primary terminals of an induction coil to some source of *alternating* current, a magneto for example, an induced current is produced without the aid of a vibrator. The alternating current, in rising to a maximum in one direction and then falling to zero, varies the strength of the magnetic field around the primary, and induces an E.M.F. in the secondary. Then it rises to a maximum in the opposite direction and falls to zero, thus inducing an opposite E.M.F. in the secondary.

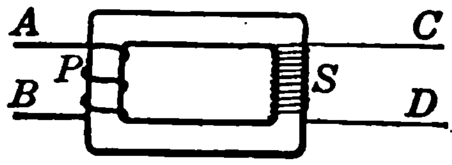


FIG. 497. — Transformer diagram.

The *voltage transformer*, which is extensively used with alternating current transmission, is a modified induction coil with the vibrator eliminated. It consists of a laminated iron ring with a few turns of heavy insulated wire wound around one section and a larger number of turns of smaller wire wound around another section. See Fig. 497. If we connect the terminals *AB* to an alternator, an induced current will be set up in the secondary coil *S*. The E.M.F.'s in the secondary and primary will have the same ratio as the relative number of turns of wire. Suppose we have 20 turns in the secondary for one turn in the primary, then the induced E.M.F. will be 20 times as high as that in the primary. A transformer that raises the voltage in this manner is called a *step-up* transformer. If we reverse the connections, then the number of turns in the secondary is less than in the primary, and the voltage is reduced. Such a transformer is a *step-down* transformer.

When the voltage in a transformer is increased, the amperage is correspondingly reduced. The efficiency of a transformer is from 95% to 98%, hence very little energy is lost. The transformer is one of the most perfect machines ever devised; it does its work silently, with little or no attention, and with an efficiency far higher than most other machines.

In the commercial transformer the two coils are usually concentric. See Fig. 498. A commercial transformer is shown in Fig. 499.

Fig. 498. — Section of transformer.

**485. Transmission of Power.** By the use of the nearly perfect transformer, alternating-current electricity can be transmitted long distances with much less expense than in the transmission of direct current. Suppose a company desires to transmit 1200 kilowatts of electrical energy from Niagara Falls to Syracuse, a distance of 150 miles. If it were transmitted at 12,000 volts, 100 amperes of current would be necessary. If the voltage were increased to 60,000 then only 20 amperes of current would be required. Such an arrangement is possible. The alternators at Niagara Falls generate electricity at 12,000 volts pressure; it is stepped up by a transformer to 60,000 volts and transmitted to the city in which the electricity is to be used; there it is stepped down by another transformer, or successively by several transformers, to any desired voltage. See Fig. 500. If this energy were transmitted at 100 amperes instead of 20, the heating effects would be 25 times as great, or $\frac{(100)^2}{(20)^2}$.

Since such energy would be wasted in heating the transmission lines, it represents considerable loss. When high voltage transmission is used, much smaller wires can be used to carry the smaller current. This represents a further saving in initial cost of installation. In all long distance transmission it is customary to use a step-up transformer, transmit the electrical energy at high voltage, and then step it down again at the end of the line to a safe working voltage. One high tension line now in use transmits electrical energy at a pressure of 150,000 volts from Big Creek to Los Angeles, California, a distance of 240 miles. In small towns electricity for lighting purposes is generally transmitted at 2200 volts and then stepped down to 110 volts before it enters dwelling houses or other buildings. The insulating towers used with a high tension line are shown in Fig. 501. The method sometimes used to insulate the cables for power transmission is shown in Fig. 502. The power

FIG. 499. — Transformer, commercial.

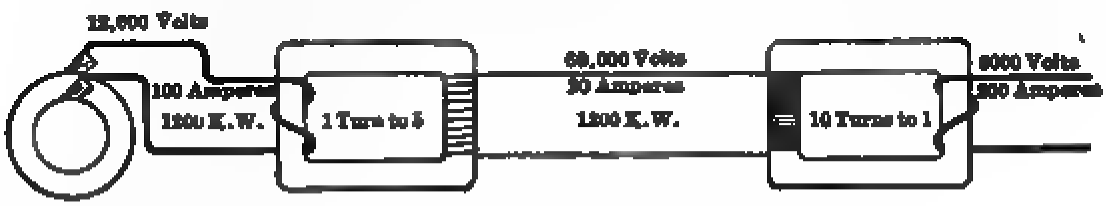



FIG. 500. — Transmission of current.

FIG. 501. — High-tension line. Note insulators, which are of the "eight-petticoat" type.

plant of the Interborough Rapid Transit Company is shown in the full-page illustration of Fig. 503.

**486. Alternating-current Power.** In the circuit of an alternating current, *self-induction* opposes the flow of the current so that it always *lags* behind the E.M.F. Therefore the power of an alternating current is not found by multiplying volts by amperes as in the case of the direct current, but by *volts times amperes times some factor*. This factor depends upon the individual circuit, but it is always less than unity. Therefore the *apparent* wattage of an alternating current is more than the *actual* wattage. Fig. 504 shows the voltage and amperage curves of an alternating current circuit. Note the *lag* of the current behind the voltage.

**487. The Choke Coil.** If a coil of wire having a low resistance but a large number of turns is connected in an alternating-current circuit, the amount of current is reduced decidedly. The self-induction occurring at each alternation produces the same effect on the current flow as a high resistance, but it does not introduce the heating effects. Self-induction in such cases is known as *reactance*. Such a coil in an alternating circuit is called a "choke coil." The current flow is reduced by both *resistance* and *reactance;* the combined effect of these two factors is called *impedance*, which we may represent by $Z$. The impedance is equal mathematically to the hypotenuse of a triangle of which the resistance and reactance are sides. Ohm's law as applied to alternating currents must be modified as follows:

Fig. 502. — Section of insulated cable.

$$\text{current} = \frac{\text{voltage}}{\text{impedance}}; \text{ or } I = \frac{E}{Z}.$$

When a "choke coil" of negligible resistance is used then the current flow is practically equal to $\frac{\text{voltage}}{\text{reactance}}$. Fig. 505 shows a "choke coil" connected in circuit with several lamps. When an iron core is introduced into the coil the *reactance* is increased and the lamps are dimmed. Coils of *varying reactance* are much used in alternating circuits.

**488. How Alternating Current Is Changed to Direct Current.** In villages and small cities alternating current is used extensively for lighting purposes. Very often it is

FIG. 503. — Power plant of Interborough Rapid Transit Company at 74th St., New York. The turbine in the foreground is 30,000 kilowatt. The 70,000-kilowatt turbine in the center is the largest in the world.

the only current available. For charging storage batteries and for some other purposes direct current must be used. There are several methods in use for changing alternating to direct current. Devices used for this purpose are often called current transformers.

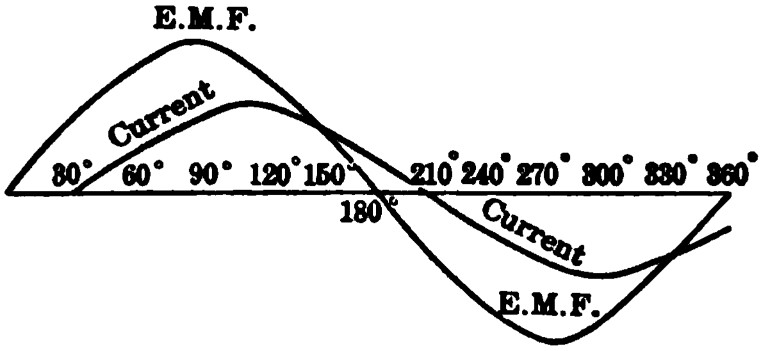



FIG. 504. — Lag curves.

The *motor-generator* is a simple method sometimes used to change or transform alternating to direct current. It consists of an alternating-current motor and a direct-current dynamo, both mounted on the same shaft. The motor uses alternating current to turn the dynamo, which generates direct current.

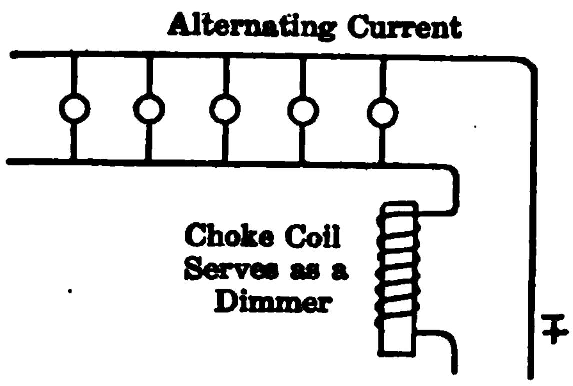



FIG. 505. — Choke coil.

The *rotary-converter* is often used to convert alternating current into direct current for street car motors. The small brick buildings frequently seen between the villages along an inter-urban line are rotary converter sub-stations. The alternating current from a high-tension line enters the armature of the converter at one end of the shaft over slip-rings and turns the armature as a motor. Direct current is taken from the other end of the armature by means of a commutator, whence it is supplied to the trolley wire directly.

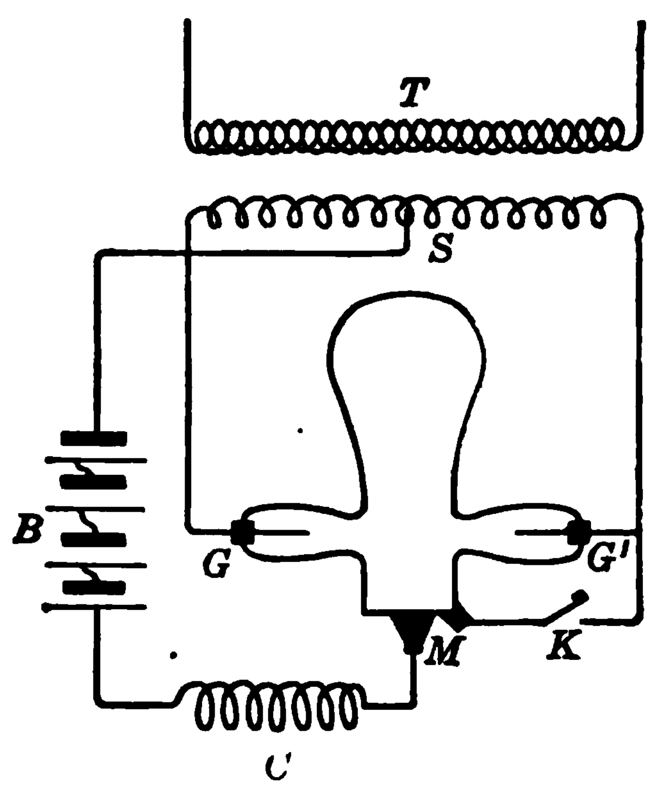



FIG. 506. — Arc rectifier diagram.

Many garages now use a *mercury-arc rectifier* for charging

storage batteries. It consists of an exhausted bulb with two graphite electrodes *GG'*, Fig. 506, and a mercury electrode *M*. When an arc has been established between the graphite electrodes and the mercury, the mercury vapor conducts the current from the graphite to the mercury but not from the mercury to the graphite. Thus an alternating current is converted into a *pulsating uni-directional* current of just half the voltage. The storage batteries *B* are connected to the secondary coil *S* of the transformer *T* and to the mercury electrode. A "choke coil" *C* is connected in series between the positive plate of the battery and the mercury electrode to prevent the "dying out" of the arc between alternations. The switch *K* is used only in establishing the arc.

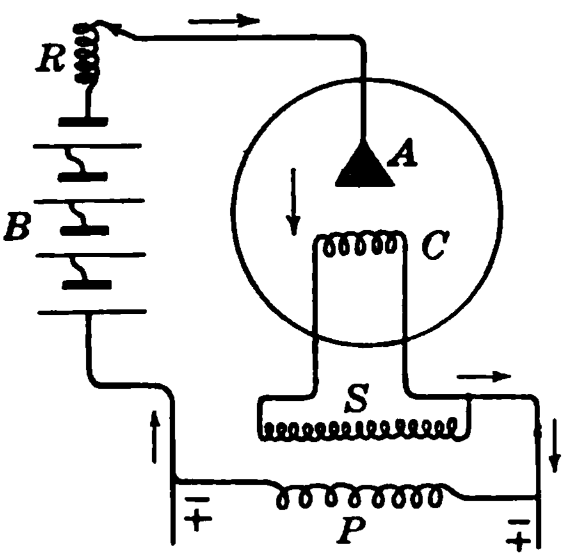


FIG. 507. — Tungar rectifier.

The *tungar rectifier* is also used for charging storage batteries. It consists of a bulb filled with argon gas at reduced pressure. The cathode *C* is a coil of tungsten wire and the anode *A* is a small cone of graphite or tungsten. See Fig. 507. When the anode has a potential several volts higher than the cathode, electrons are discharged from the cathode if it is highly heated. These electrons split the argon molecules into positive and negative ions which conduct the current through the bulb. The cathode is heated by the alternating current which is so connected with the bulb that the anode *A* and the cathode *C* are alternately (+) and (−). Electrons are discharged only when the cathode is (−). When the anode is (−) no molecules are ionized. Therefore the alternating current is changed into a *pulsating* current flowing in one direction only.

**489. Three-wire System of Wiring.** When direct current is used for incandescent lighting, either the Edison three-

wire or the five-wire system is more economical than the two-wire system. Direct current for lighting is generally used when the current is generated in the same building or in the immediate vicinity. We have already learned that it is cheaper to transmit alternating current than direct if the distance is considerable. In the three-wire system two

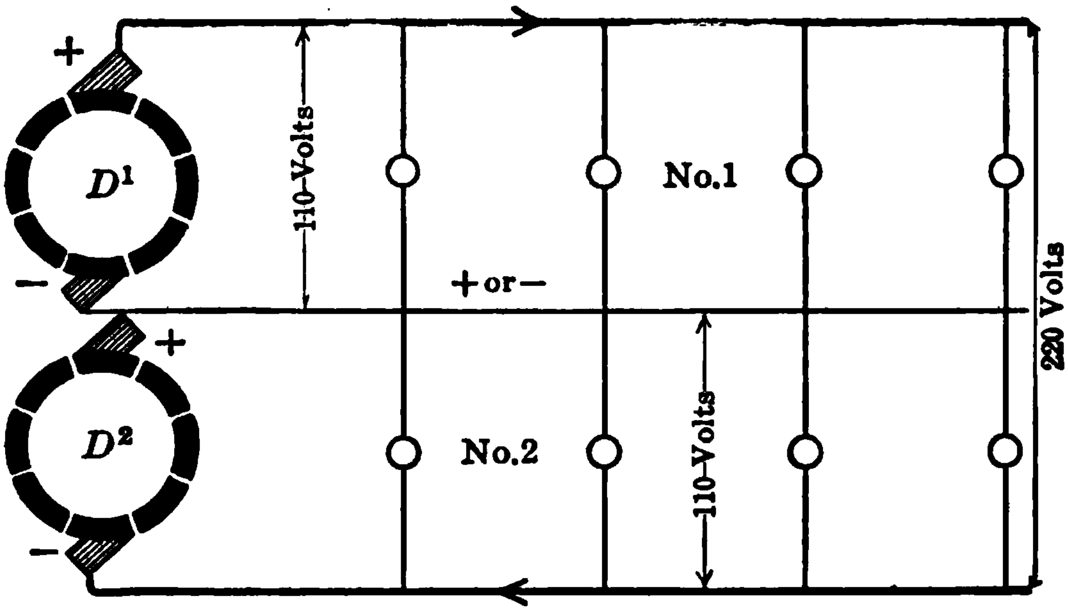



FIG. 508. — Three-wire wiring system.

dynamos are connected in series as in Fig. 508. If the same number of lamps are in use on both sides no current flows through the middle wire, which is called the neutral. Suppose one light is turned off on the No. 1 side, then the current for the unbalanced lamp flows through the neutral wire from the plus brush of dynamo No. 2. The middle wire is then positive. If two lamps on No. 2 circuit are turned off, then the current from two unbalanced lamps on the other side flows from the plus terminal of dynamo No. 1, and returns through the "neutral" wire which is now negative. This system uses about half as much wire as the two-wire system. The voltage between the outside wires is 220.

## SUMMARY

An induced E.M.F. is produced by varying the strength of the magnetic field in which the conductor is placed. The magnetic

field may be varied by the use of the "make" and "break"; by an alternating current; or by an iron disc moving in the magnetic field, as with the simple telephone.

The induction coil is used for ignition purposes in gas engines, for medical batteries, for X-ray work, and for wireless.

The voltage transformer raises or lowers the voltage of an alternating current. A step-up transformer raises the voltage; a step-down transformer lowers the voltage.

Ohm's law does not apply directly to alternating currents, since they are influenced so much by reactance or self-induction.

Alternating currents may be converted into direct currents by motor generators, rotary converters, mercury-arc rectifiers, or tungar rectifiers.

## QUESTIONS AND PROBLEMS

1. Outline as many methods as you can for producing an induced E.M.F.

2. How does an induced E.M.F. differ from an induced current?

3. Draw a diagram to show how gas-jets could be connected with a coil and battery to make them self-lighting.

4. Can you see any reasons for using oil in voltage transformers?

5. Eddy currents in the "former" of a galvanometer coil prevent vibrations and bring the coil to rest quickly. Such a galvanometer is called "dead-beat." Explain the action.

6. Why are the coils of a rheostat wound back upon themselves as in Fig. 454?

7. Summarize the advantages of the alternating current. Summarize the advantages of the direct current.

8. From the principle of self-induction explain why a shunt-wound motor will not run on an alternating current, while a series-wound motor will run on either direct current or alternating current.

*Suggested Topics.* High-tension Power Transmission. Microphone. Dictaphone.

## CHAPTER 28

# WIRELESS TELEGRAPHY — X-RAYS — RADIO-ACTIVITY

### A. WIRELESS TELEGRAPH AND TELEPHONE

**490. Electrical Discharge Oscillatory.** Photographs have been taken which show that the discharge from a Leyden jar or from a spark coil is oscillatory. These oscillations, which vary in frequency from one thousand to several million per second, set up waves in the ether. These waves travel in all directions with the same velocity as that of light. They may be refracted and reflected as in the case of light waves. While some substances are opaque to these waves, yet most substances, even solids that are opaque to light, are transparent. Since Hertz in 1888 detected and measured such ether waves, they are often called Hertzian waves.

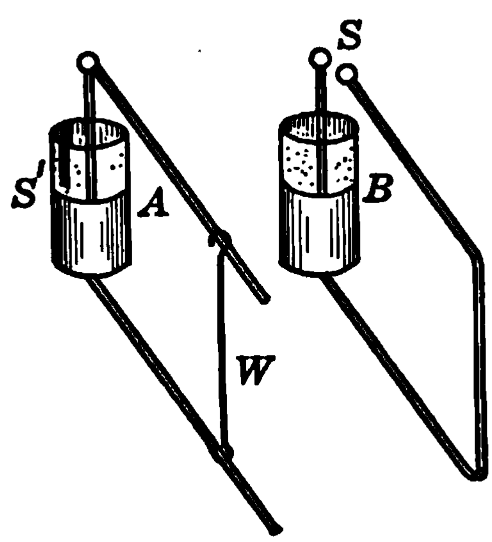


FIG. 509. — Electrical resonance.

**491. Electrical Resonance.** In the study of sound we learned that one tuning fork can throw another fork of the same frequency into sympathetic vibration, even if the forks are some distance apart. Such *sympathetic vibrations* afford an excellent example of *resonance*.

Suppose we connect the two coats of Leyden jar $A$ by a loop of wire as shown in Fig. 509. The wire $W$ is so adjusted that it may be slid back and forth, thus changing the length

of the loop. One end of a piece of tin-foil is connected with the inner coating of the jar; it is then bent over the top of the jar in such a way that the other end lacks about one millimeter of touching the outer coat. Next let us fasten one end of a loop to the outer coat of an exactly similar jar *B*; the other end of the loop is brought near the knob of the jar as shown at *S*. The jars are placed near each other with their loops parallel, and the coatings of the jar *B* are connected with the secondary of an induction coil or with the terminals of a static machine. When the induction coil is in operation, an electrical discharge occurs between the knobs at *S*. If we adjust the slide wire *W* until the areas of the two loops are equal, an electric spark also occurs simultaneously at *S'*. If the areas of the loop are made unequal, then a spark at *S* does not produce a spark at *S'*. This experiment is an example of *electrical resonance.* The two electrical circuits are *tuned* by adjusting the loops until they have the same area. Such *tuning* is analogous to the sympathetic vibrations impressed upon one tuning fork by another of the same frequency. Electrical resonance is also a proof of the oscillatory nature of the electric spark. Wireless telegraphy depends upon the production of Hertzian waves by means of an oscillatory spark, and the use of some device which is tuned to receive such waves.

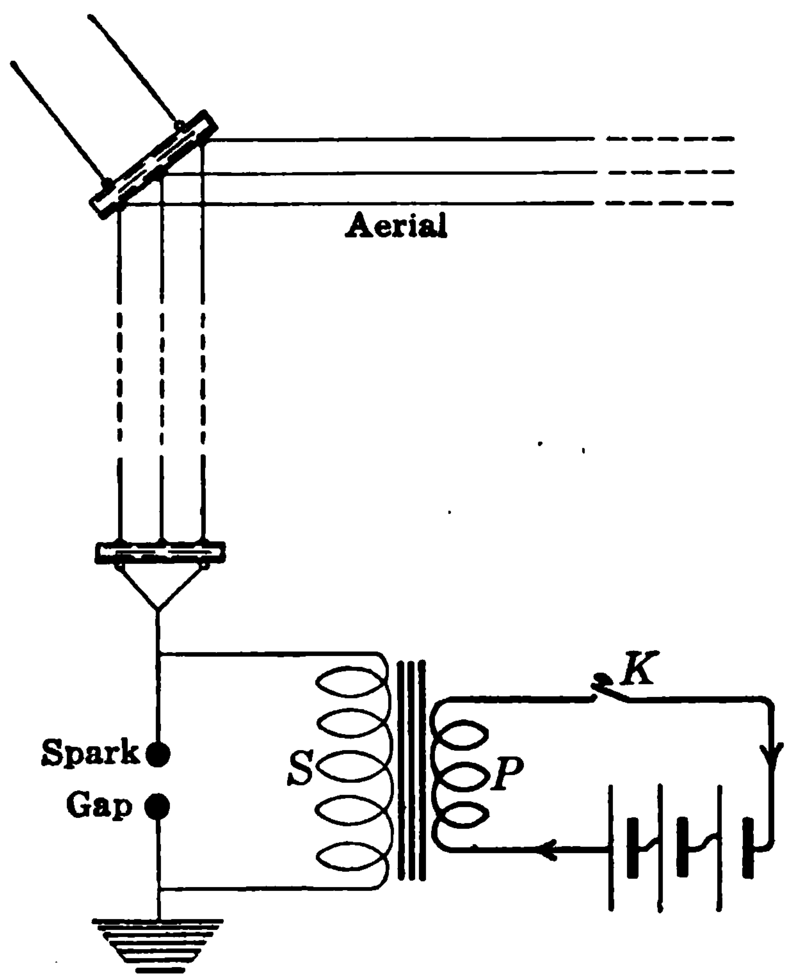



FIG. 510. — Transmitting system, wireless.

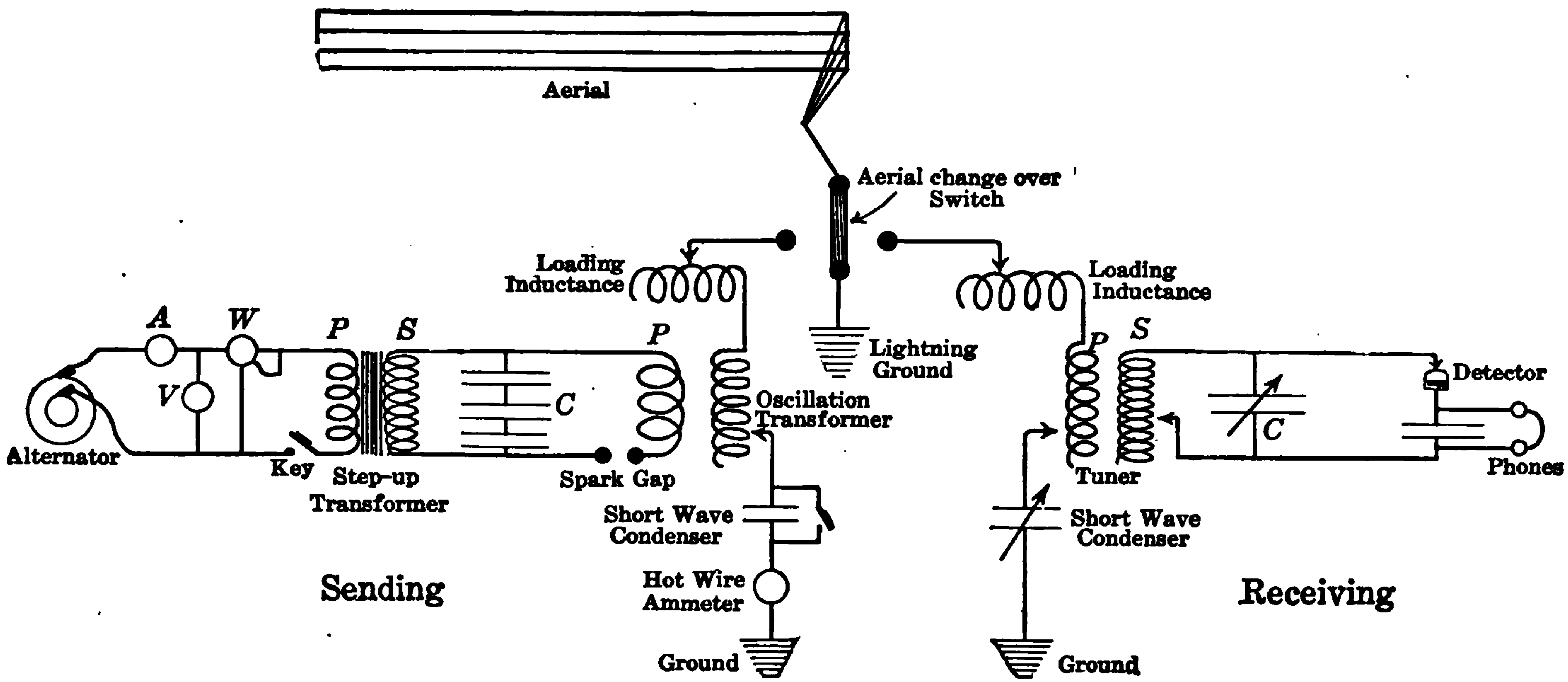



FIG. 511. — Wiring diagram of commercial station. $V$, voltmeter; $A$, ammeter; $W$, watt-hour meter; $P$, primary of transformer; $S$, secondary of transformer; $C$, condenser. An arrow across a condenser shows that its capacity can be varied.

**492. Wireless Telegraphy. Transmission.** By using a Morse key in series with a battery and the primary of an induction coil, successive sets of waves may be radiated from the oscillatory spark of the secondary. These trains of waves thus become definite signals, dependent upon the duration of the impulse. One terminal of the secondary coil is grounded and the other terminal is connected to an aerial, if the ether waves are to be transmitted to any considerable distance. Fig. 510 shows one of the simplest devices for transmission.

In commercial transmitters an alternator is connected in series with a key $K$ and the primary of a transformer. See Fig. 511. The voltage of the alternator is thus stepped up to from 5000 to 20,000 volts in the secondary $S$ of the transformer. This high voltage charges the condenser $C$ until its potential is high enough to produce an oscillatory spark at the gap $G$. The frequency of this spark depends upon the capacity of the condenser and upon the inductance of the variable coil; it varies from 20,000 in transatlantic stations to 1,500,000 in short wave amateur stations. The oscillations pass through the primary of the "oscillation transformer," inducing in the secondary oscillations which surge through the aerial system.

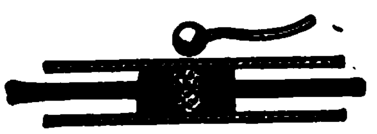


Fig. 512. — Coherer.

**493. Receivers or Detectors.** In 1894 Marconi devised the *coherer*, the earliest form of wireless detector. It consists of a small tube containing a mixture of metal filings as shown in Fig. 512. Two metal plugs form the terminals; these plugs are connected in series with a battery and a relay, which acts as a circuit closer through a telegraph sounder. The filings offer so much resistance that the battery current is too feeble to operate the relay. Hertzian waves from an oscillatory spark cause the filings to cohere, thus decreasing their resistance so much that the relay closes the sounder circuit and a signal is produced. Then an

**Sir William Crookes.**

Crookes' tube. Methods of producing high vacua.

**Wilhelm Konrad Roentgen.**

Discoverer of X-rays.

**Heinrich Rudolf Hertz.**

Discoverer of Hertzian waves.

**Guglielmo Marconi.**

Inventor of wireless telegraph.

automatic tapper strikes the tube and causes the filings to *decohere,* so the next signal may be received. One terminal of the coherer is grounded and the other is connected to an aerial system.

The coherer is now obsolete and several improved detectors are in use. *Crystal detectors* are now used extensively by amateurs. A small block consisting of galena, selenium, silicon, carborundum, or other crystal is embedded in a metal block which is connected in circuit with a telephone receiver. The circuit is completed though a condenser and a metal wire which presses against the crystal detector. The principle of such a detector is one of *uni-lateral conductivity.* The crystal permits current to flow in one direction through it, but offers great resistance to a current flowing in the opposite direction. Some crystals offer several thousand times as much resistance to a current flowing in one direction as they do to a current flowing in the opposite direction. Fig. 513 shows how the connections are made for a simple form of wireless receiving outfit. *D* is the detector; *B* is a variable inductance coil connected with the aerial system. *B′* is then balanced with *B* by varying the inductance of the coil and the capacity of the condenser *C,* which is connected in shunt across the terminals of the coil *B′*. Bulbs of the *audion* type are now extensively used as detectors for commercial work in both the wireless telegraph and the wireless telephone. They do not differ in principle from the tungar rectifier described in § 488.

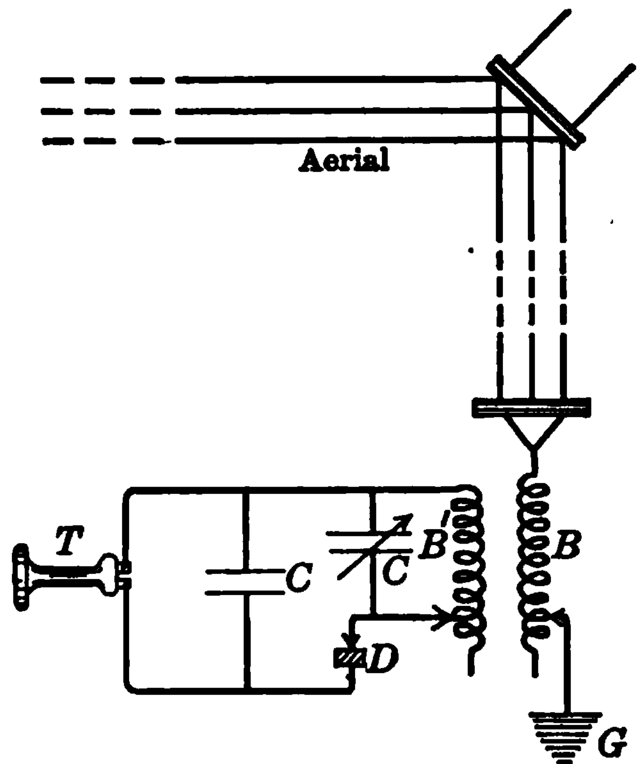



FIG. 513. — Receiving system, wireless.

The wiring diagram of an *audion* bulb as used in a receiving circuit is shown in Fig. 514. Such a bulb is sometimes known as a *thermionic* (ionized by heat) tube. The filament *F* emits electrons when it is heated to incandescence. The plate *P* is charged at a higher potential, hence a stream of electrons flows from the filament to the plate. Suppose we

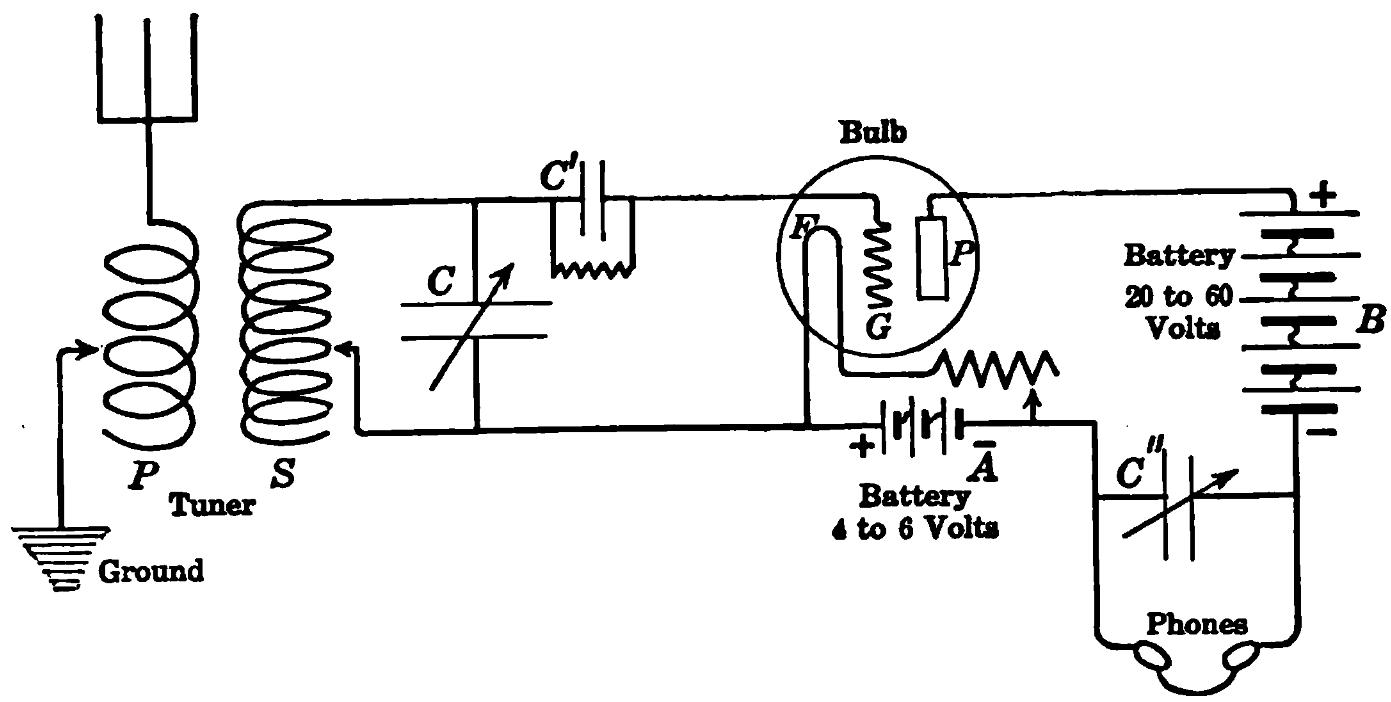



FIG. 514. — Wiring diagram of an *audion* bulb as used in a receiving circuit.

put a fine wire metallic grid *G* between the filament and the plate. The grid does not interfere with the flow of electrons unless it is charged negatively with respect to the filament; then it repels the oncoming electrons. Thus a small amount of energy may so charge the grid that it is able to control a very large amount of energy flowing from the filament to the plate. The incoming wave-trains from the secondary of the tuning coil act through the condenser on the grid, giving it a negative potential. Such a train of waves may be too feeble to produce an audible sound in the telephone, but it varies the larger battery circuit, which yields audible signals exactly corresponding to the incoming waves.

Regenerative receivers are now extensively used. In such receivers, the oscillating currents in the plate circuit are fed back to amplify the currents in the grid circuit. Regeneration may be secured by connecting a variometer, or a

variable inductance in the plate circuit, or a coil similar to the secondary may be put in the plate circuit. Such a coil is known as a feed-back, or tickler coil.

In a commercial receiving system the aerial system is tuned to resonance with the transmitting system by an inductance coil and a variable condenser *C*. See Fig. 511. The arrows drawn diagonally show that the condensers are variable, and that the coils are loose coupled; that is, the interaction of the circuits can be varied by sliding one coil inside the other. When the receiving apparatus is tuned in this manner, ether waves of other lengths do not interfere.

**494. Wireless Telephone.** Commercial wireless telegraph stations usually transmit waves of high frequency. Since these waves are produced by a high frequency alternator with a rotary spark-gap, the *train of waves* is unvarying; hence it produces a musical note in the telephone receiver. If a *microphone transmitter* is introduced in the circuit, the train of waves may be modified by the sound waves entering the transmitter to correspond to the human voice or to other sounds. Any wireless telegraph station may be tuned to receive the spoken messages.

**495. Commercial Importance of Wireless.** Since the epochal discovery of Marconi, wireless telegraphy has become an important commercial factor and the use of wireless communication has grown by leaps and bounds. The wireless outfit soon became an instructive plaything for boys, and an instrument for various types of commercial transactions, or for the use of governments in directing battleships or armies. Practically all ocean vessels are now equipped with wireless apparatus; they are in daily communication with other ships and with the land. To avoid interference the *International Radio Congress* established rules regarding the length of waves that may be used for transmission. Amateurs may not use wave lengths of more than 200 meters; the government reserves for its own use

wave lengths from 600 meters to 1600 meters; wave lengths varying from 300 to 600 meters or above 1600 meters may be used by commercial companies. The wave length is approximately four times the combined length of the aerial wires. The French government uses the Eiffel tower to support the aerial of a very powerful wireless station. Communication between this French station and the United States government station at Arlington is very easy. Time signals are sent out daily. The Radio Corporation Station on Long Island is the largest in the world. It consists of six

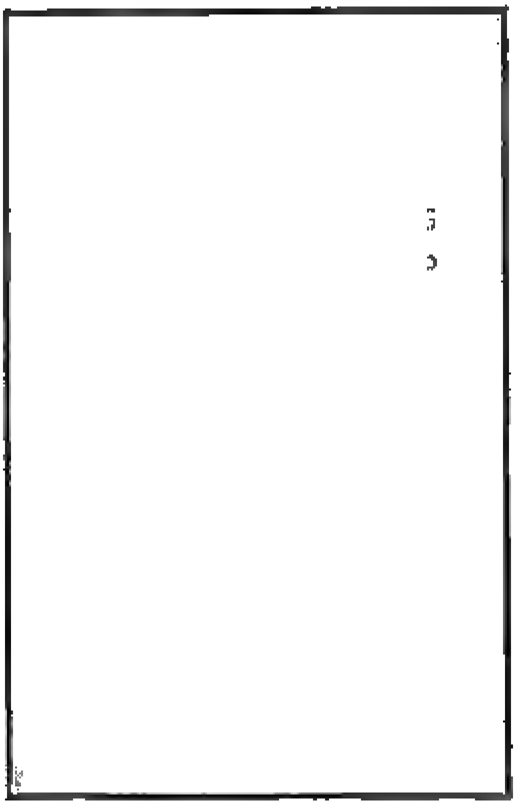


Fig. 515. — Amplifier tube, for receiving. *F*, filament; *G*, grid; *P*, plate.

Fig. 516. — Amplifier. For transmission.

units, one of which is always kept in reserve. The other five units can all be operated as a single unit, or they may be operated separately, thus making possible communication with five widely separated countries at the same time.

It is impossible to measure the value of the wireless telegraph or telephone as used in the World War. In fact

the wireless telephone was not well developed commercially before the war; during the war it was very extensively used to direct air-planes, in controlling the movement of vessels, and for various other purposes. The audion amplifier of DeForest was used in 1914 for telephoning from New York to San Francisco. Fig. 515 shows an amplifying bulb that is used as a receiver in wireless telephony. Fig. 516 shows an amplifier that is used for transmission work. The next year, by the use of such an amplifier at the government station at Arlington, telephonic messages were transmitted which were received at Paris and at Honolulu; the messages were so clear that the voices of the speakers at Washington could be distinctly recognized. Weather observations are now reported by wireless daily in the United States. In connection with the aviation service, the weather observations are now taken by the Army and Navy Departments.

**496. Radio Broad-casting.** Before the World War a few boys in nearly every neighborhood made wireless sets, learned the wireless code, and communicated with one another every evening. In many cases the sets were merely toys, but some of the boys became quite proficient and were able to render excellent service later to their country. When the United States entered the war, these amateur stations were dismantled. Radio engineers accomplished wonders during the war in developing wireless *telephony.* Now any one may "listen in," whether he knows the code or not. Broad-casting stations have sprung up all over the United States. From such stations music, time signals, baseball scores, reports of athletic games, bed-time stories, political campaign speeches, and sermons are broad-casted.

The radio transmitter is essentially a generator of *radio-frequency currents.* Such a generator supplies alternating current at a frequency of more than 10,000 cycles per second. Suppose we wish to send out waves 200 meters long. The velocity of electricity is the same as that of light, 300,000,000

meters (186,000 mi.) per second. Since $v = nl$, we find that a generator must have $\frac{300,000,000}{200}$, or 1,500,000 cycles per second to produce waves of that length.

If the frequency falls below 10,000 cycles per second, *audio-frequency currents* are produced. They are known as

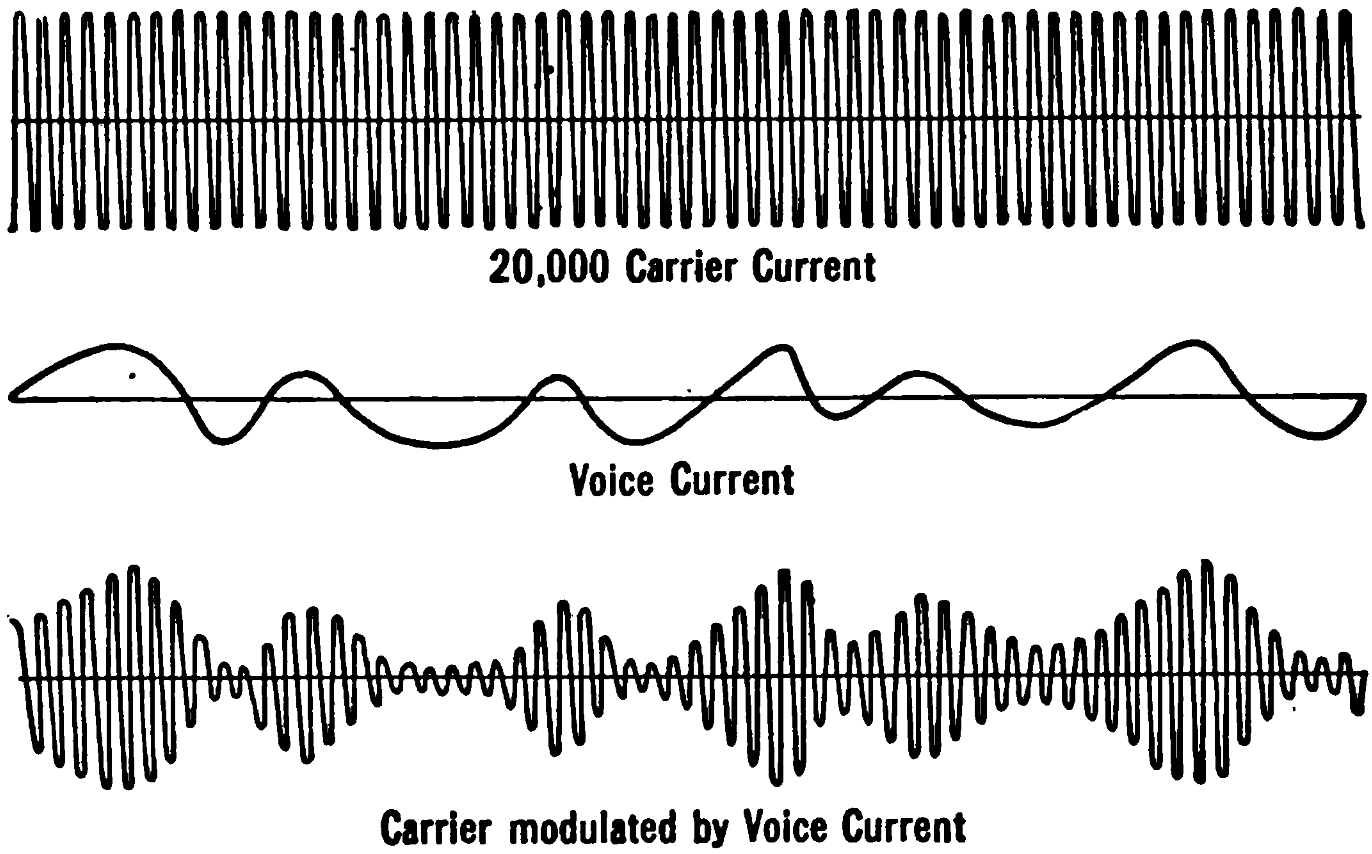



FIG. 516 *a*. — Continuous radio-frequency wave, modulated by voice current

audio-frequency currents because they produce waves to which the ear is sensitive, and they are audible in the telephone receiver.

Fig. 516 *a* shows the *carrier wave* produced by a generator having a frequency of 20,000 cycles. The wave is *undamped*, or *continuous*. It has the same amplitude throughout; hence it is suitable for wireless telephony. In *damped*, or *discontinuous*, waves the amplitude decreases. The same figure shows the *voice wave* alone, and also the effect that it produces in *modulating* the carrier wave. The sound waves are introduced by a microphone operating in conjunction with a thermionic amplifier. All public broad-casting stations use

a wave length of 360 meters with sufficient energy to cover a radius of 50 miles or more; the distance depends upon the hour of the day, the time of year, and certain other conditions.

**497. The Receiving Set.** The thousands of amateur receiving sets now in use vary greatly, from simple home-made sets costing a few dollars to the more complicated apparatus purchased for a hundred dollars or more. The principles involved are the same in any case. The following parts may be studied with further reference to the principles of electricity:

*Aerial.* Since the aerial or antenna should have low resistance, it is generally made of copper wire or phosphor bronze, from No. 14 to No. 18 B. & S. gauge. Its length depends upon the length of the wave to be received. For example, a single vertical wire 100 ft. long will have a natural wave length of 400 ft., or about 120 meters. A four-wire horizontal aerial with wires about 2½ ft. apart will have a natural wave length of from 4.4 to 4.8 times its total length, measured from the extreme end of the antenna down to the apparatus. The capacity of a four-wire aerial is slightly more than that of a two-wire, but its inductance is less. Fire escapes, bed-springs, etc., have been used as antennæ with considerable success.

*Grounding.* It is very important that the ground system have a high capacity. Connecting the ground wire to a water-pipe system makes it possible to secure sufficient capacity. It is not so satisfactory to connect to the gas-pipes. A number of wires spread out on the ground underneath the antenna reduces the resistance of the antenna materially.

*Detectors.* Several types of detectors were discussed in § 494. The detector serves to rectify the alternating current; with bulbs amplification also occurs.

*Condenser.* The use of the condenser to increase the capacity of a conductor was studied in § 407. The unit

of capacity is the *farad*, named in honor of Michael Faraday. A condenser has a capacity of one farad, if it give a pressure of one volt when charged with one coulomb of electricity. The *coulomb* is the unit of electrical quantity; it is the amount of electricity transferred by a current of one ampere flowing for one second. The farad is such a large unit that the micro-farad, which is one millionth of the farad, is generally used in wireless as a capacity unit. Paraffined paper, hard rubber, mica, and air are generally used as dielectric material in condensers. Mica is especially good, since it is not easily ruptured by high voltages. Three types of condenser are used in wireless work: fixed, adjustable, and variable. The capacity of the fixed condenser cannot be altered. With an adjustable condenser, the capacity may be varied by successive steps. Any capacity between the minimum and maximum may be obtained by means of a variable condenser. The air condenser, in which aluminum plates rotating on an axis may slide between stationary plates of the same material, is a common example of the variable condenser.

*Inductance Coils.* Inductance coils, or loading coils, are used to increase the natural wave length of the antenna. The honey-comb inductance coils have a duo-lateral winding. The turns of one layer cross the preceding layer always at an angle. This gives a compact coil of a cellular type. The distributed capacity, or self-capacity, is thus reduced to a minimum. The *henry* is the unit of inductance; it is equal to an induced pressure of one volt when the inducing current varies at the rate of one ampere per second. The *milli-henry* and the *micro-henry* are the more common units used for wireless work.

*Tuning Coils.* The slide tuning coil is very simple, consisting of an inductance coil with one or more sliding contacts to vary the inductance. The loose-coupler consists of two

concentric coils, so mounted that one coil may be slid inside the other. The inductance of the primary may also be varied by a sliding contact.

*Phones.* The head-phones used for receiving wireless signals have a high resistance, usually 2000 ohms or more. If they are wound with enough copper wire to give a resistance of 2000 ohms, the reactance may be great enough to bring the impedance up to 20,000 ohms. See § 487. Just as voltaic cells work better when so grouped that the total internal resistance equals the external resistance, so it has been found that the phones work most satisfactorily when their impedance is as nearly equal as possible to that of the rest of the circuit.

*Loud Speaker.* The loud speaker consists of an enlarged form of telephone receiver to which an amplifying horn is attached. The receiver is connected with vacuum tube amplifiers.

*The Battery.* Dry cells may be used for the *A* battery in a bulb circuit. Four dry cells in series (6 volts) furnish enough current to heat the filament and cause the emission of electrons. A storage battery is more satisfactory, both for the *A* battery, and in some cases for the *B* battery, which needs from 20 to 40 volts. When storage batteries are used they must be recharged at intervals of from two to four weeks, if used a couple of hours daily. In § 488 we studied several methods of changing alternating current to direct current. The tungar rectifier is one method commonly used for charging storage batteries.

*Nodon Valve.* The electrolytic rectifier, or Nodon valve, is quite satisfactory, and it can be made at little expense. This rectifier consists of a plate or rod of aluminum and one of lead immersed in a jar containing a saturated solution of baking soda, ammonium phosphate, or borax. When the current is turned on, oxygen and hydrogen gases are liberated. These gases unite with the aluminum to form a layer

of aluminum hydroxide on the surface of the aluminum plate. This hydroxide layer acts as a valve, permitting current to flow from the aluminum to the lead, but not in the opposite direction. Thus the alternating current is changed into a direct current.

## *B.* X-RAYS

**498. Electrical Discharge in Partial Vacua.** We have learned that a pressure of 27,000 volts is necessary to produce a spark 1 cm. long across an air-gap; if the terminals of the secondary of an induction coil are pointed, a pressure of only about 8000 volts is needed to produce a spark of that length. Suppose we have a tube two or three feet long with metal terminals sealed in each end. If we connect it to the secondary of an induction coil as in Fig. 517, the spark takes the short path $AB$ as the discharge occurs. If we pump out some of the air from the glass tube, the discharge then occurs between the terminals $A'B'$, and the whole tube becomes filled with a bluish-violet light.

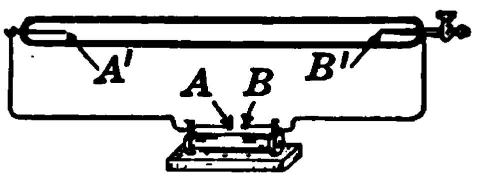


FIG. 517. — Partial vacuum tube.

This experiment shows that the resistance offered by a partial vacuum is decidedly less than that of a very much shorter air-gap.

The color of the light may be varied by filling the tube with rarefied gases, such as hydrogen, nitrogen, chlorine, etc. Very beautiful effects may be produced in a darkened room by using different gases in vari-colored glass tubes. Such tubes are known as Geissler tubes. See Fig. 518.

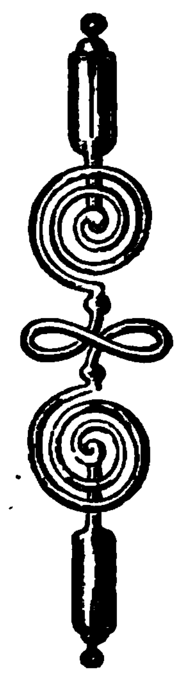


FIG. 518. — Geissler tube.

Tubes of this nature filled with *neon* gas are used for testing spark plugs. When one end of the tube is held against the plug, a crimson light may be observed, if the spark-plug is firing properly.

**499. Cathode Rays.** When a glass tube of the form shown in Fig. 519 is attached to the terminals of an induction coil and the atmospheric pressure in the tube is reduced to less than 0.001 mm. of mercury, an invisible radiation called the cathode rays is given off from the cathode at nearly right angles.

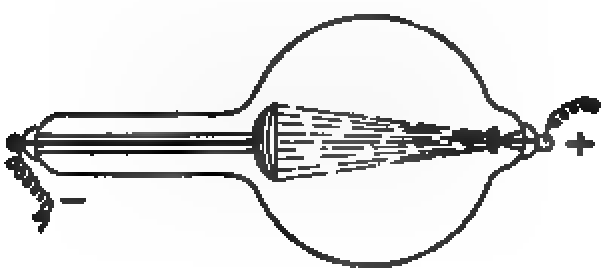


FIG. 519. — Cathode tube.

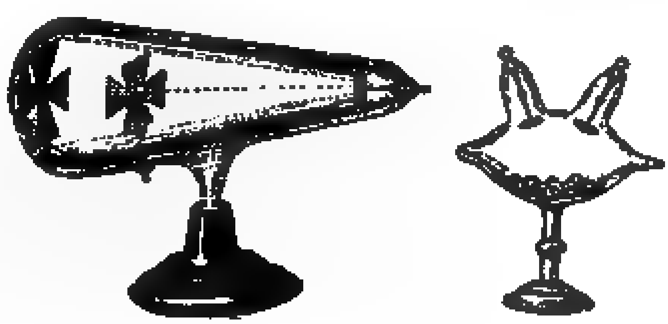
The presence of these *cathode rays* may be detected (1) by their heating effects; (2) by their fluorescent effects; and (3) by the shadows they produce.

(1) If a piece of tungsten is sealed in the tube of Fig. 520 so that these rays may be concentrated upon it, the bombardment of the rays heats the tungsten white hot in a short time.

(2) As the cathode rays fall upon the glass tube a yellowish green fluorescence is produced. Pieces of zinc sulphide or of colored glass also fluoresce readily when exposed to the cathode rays in an apparatus like that shown in Fig. 521 *B*.

FIG. 520. — Heat effects of cathode rays.

(3) If a piece of metal is interposed in the path of the rays as in Fig. 521 *A*, a shadow is produced. The glass fluoresces on all sides, but directly back of the metal it is dark; this shows that the cathode rays have been intercepted by the metal plate.



*A* *B*

FIG. 521. — Shadow effect of cathode rays.

**500. Nature of the Cathode Rays.** A piece of metal containing a narrow slit may be placed in the path of the cathode rays so that a single stream of rays passes through the slit as shown in Fig. 522. If a magnet is held near the tube, the cathode rays are deflected, such deflection becoming visible by the fluorescence of a screen placed in the tube. As a result of this and other experiments it has been found that the *cathode rays are negatively charged particles given off from the cathode.* J. J. Thomson calls these particles *electrons.* Their mass has been determined; it is about $\frac{1}{1800}$ as great as the mass of the hydrogen atom, which is the lightest atom known. The speed of the cathode particles varies from 20,000 miles to over 100,000 miles per second.

FIG. 522. — Effect of magnet on cathode rays.

**501. X-rays.** The X-ray bulb differs little from the Crookes tube which is used to produce cathode rays. If a tungsten or platinum disc is placed in a cathode bulb in such position that the cathode rays are concentrated upon it, a different type of invisible radiation is produced, Fig. 523. These radiations are called *X-rays*, or they are sometimes called from their discoverer, the Roentgen rays. The X-rays differ from the cathode rays since they are not affected by a magnet. Unlike light rays they cannot be reflected or refracted; hence they cannot be focused. It is quite certain that the X-rays consist of very short waves set up in the ether by the bombardment of the cathode particles upon the metal disc.

FIG. 523. — X-ray bulb.

**502. Uses of X-rays.** The most important use of X-rays depends upon their ability: (1) to affect a photographic plate; (2) to penetrate various kinds of matter which is opaque to light, such as wood, flesh, leather, etc. Their penetrating power depends upon the degree to which the bulb producing them is exhausted, and upon the voltage used. The rays from a very high vacuum bulb are very

FIG. 524. — Radiographs. The cut at the left was made by the action of radium rays. The one at the right by the X-rays. (*Courtesy of Radium Limited, U. S. A.*)

penetrating; they are called "hard rays." The less penetrating rays produced by a bulb with lower exhaustion are called "soft rays." The X-rays do not penetrate bones and metals as readily as they do wood and fleshy tissues.

These properties of X-rays make them very useful to surgeons in studying the fractures of bones and in locating foreign substances in the body. X-ray photographs are taken by placing the object on the cover of the holder in which the plate is enclosed and then bringing the X-ray tube a few inches from it. Such photographs are called *radiographs* or *skiagraphs*. Since the rays are not focused, the picture

is only a shadow picture. The bones and metallic objects are darker, since they absorb the X-rays more readily. See Fig. 524. Before radiographs of the stomach and intestinal tract are taken, the patient is given large doses of buttermilk containing barium sulphate and bismuth subnitrate in suspension. These heavy solids cause the outline shadows of these organs to become very distinct. Cancer on the walls of the stomach shows so clearly that 90% of the diagnoses following X-ray examination prove correct.

The X-ray is used by a large shoe company to test shoes to see if the nailing is properly done. Department stores sometimes use the X-ray to aid in fitting shoes, but they do not use it with cheap shoes. Pearls are nearly transparent to the X-rays, but imitation pearls are decidedly dark by contrast. The X-ray has also been used with considerable success in determining whether paintings are the work of the old masters or mere copies.

FIG. 525. — Fluoroscope.

**503. The Fluoroscope.** To study the effects of the X-rays without photographing them, the fluoroscope is used. It consists of a box with opaque sides and a screen of some fluorescent substance like platinum-barium-cyanide or zinc sulphide. By its use the bones of the hand become visible by holding the hand between the fluoroscope screen and an X-ray tube. See Fig. 525. A woman, thought to have a tumor, was placed before such a screen. It was not a tumor, but a hair-ball, which was later removed from the stomach.

**Marie Sklodowska Curie** (1867– ) was born in Poland. After Henri Becquerel discovered the radio-activity of uranium, Mme. Curie in collaboration with her husband, Pierre Curie, examined other substances to learn whether they are radio-active. From pitchblende she isolated radium. She also discovered polonium. In 1903 M. and Mme. Curie shared the Nobel prize with Becquerel. The College women of America presented Mme. Curie with one gram of radium to be used for research work.

**James Clerk-Maxwell** (1831–1879) was a Scotch physicist. In 1873 he published a treatise on "Electricity and Magnetism." He believed that electro-magnetic energy travels through space in the same manner as light and at the same velocity. His electro-magnetic theory has been confirmed by experiment, and by the discovery of the Hertzian waves. Maxwell investigated the nature of color and the kinetic theory of matter.

## C. RADIO-ACTIVITY

**504. Radio-activity.** In 1896 Henri Becquerel discovered that uranium affects a photographic plate through opaque paper. He wrapped a photographic plate in opaque paper, placed a coin upon it, and then suspended a piece of uranium over the coin. When the plate was developed after a few days, a picture of the coin was found upon it. These radiations emitted by the metal uranium are very much like the X-rays in their ability to penetrate opaque substances. Like the X-ray they also discharge an electroscope very rapidly. Substances like uranium that give off radiations of this nature are said to be *radio-active.*

**505. Discovery of Radium.** Soon after Becquerel's discovery that uranium is radio-active, Madame Curie began to examine other elements for radio-activity. Of the then known elements she found only one element besides uranium that has this property, namely thorium, an element used in making the Welsbach gas mantles. She did find, however, that pitchblende, a mineral from which uranium is obtained, is four times as active as uranium itself. She therefore concluded that this mineral must contain some element far more active than uranium. From several tons of pitchblende she succeeded in extracting a few milligrams of an element more than 1,000,000 times as active as uranium. She named the element *radium.* Radium is usually used in the form of its salts, especially the chloride, bromide, and carbonate. The element itself was not extracted until the year 1910. Both the metal and its salts produce the so-called *Becquerel rays.*

**506. Radium.** In many respects radium is the most interesting element ever discovered. Its properties are unusual and it *does* things. (1) It affects a photographic plate, even through opaque substances like paper, wood, and thin sheets of metals, Fig. 524. (2) Radium and its compounds discharge an electroscope; they knock to pieces

air molecules, breaking them up into ions and thus rendering them conductors. (3) Radium produces fluorescence with certain substances; when radium salts are mixed with zinc sulphide, a mixture is formed that is luminous in the dark. Such a mixture is used as luminous paint for coating the dials of air-plane instruments, the hands and dials of watches, and the sights of guns that are to be used for night firing. (4) Radium is active chemically; it decomposes water, changes oxygen to ozone, imparts a purple color to glass, etc. (5) Radium produces a physiological effect; it produces frightful burns that require a long time to heal. Many early investigators were severely burned by radium while experimenting with it. Scientists have made much progress in the use of radium for the treatment of cancer and certain other diseases. The rays which produce the more dangerous burns are screened out; the other rays may then be used to destroy the cancerous tissue. It destroys the germinating power of seeds, destroys bacteria, and kills some small animals. (6) Radium glows in the dark, producing a pale phosphorescence. (7) Radium gives off enough heat every hour to melt 1.5 times its own weight of ice; this heat is given off almost continuously, since radium loses only one half its energy in 1700 years, one half of what remains in the next 1700 years, and so on. Radium is very rare and expensive; the chloride of radium costs about $120 per milligram, or more than $3,000,000 per ounce.

**507. Nature of the Becquerel Rays.** The Becquerel rays that are emitted by such elements as uranium, thorium, and radium have been very carefully studied. In 1899 Ernest Rutherford, then of McGill University, discovered that the Becquerel rays are complex, consisting of three different classes:

(1) The $\alpha$-rays, or *alpha rays*, are identical with *positively* charged helium atoms. Their mass is nearly four times

that of the hydrogen atom; their velocity is from 10,000 to 20,000 miles per second. The alpha rays do not have as great penetrating power as the other rays; a very thin piece of aluminum foil or a thin sheet of paper is sufficient to intercept them. On the other hand, they are very efficient in ionizing air molecules; hence they discharge an electroscope rapidly. Severe radium burns are largely due to the alpha rays.

(2) The $\beta$-rays, or *beta rays*, are identical with the cathode rays. They consist of negatively charged particles of matter, or electrons. They are only about $\frac{1}{1800}$ as heavy as the hydrogen atom. Since they travel at a velocity of from 60,000 miles per second to 160,000 miles per second, they have much greater penetrating power than the alpha particles. The $\beta$-ray seems to be identical with the charge carried by the negative ion in solution or during electrolysis.

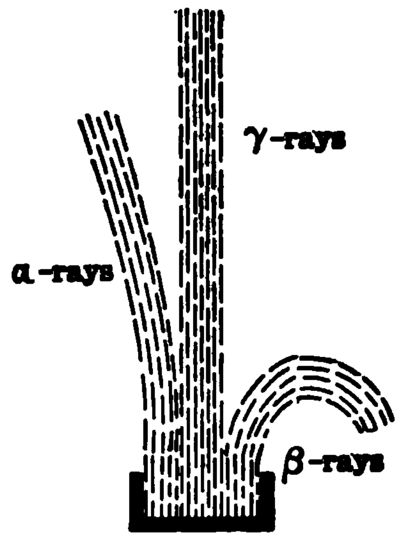


FIG. 526. — Effect of magnet on rays.

(3) The $\gamma$-rays, or *gamma rays*, appear to be of the same nature as the X-rays. They are more penetrating than either the alpha or the beta rays. The gamma rays are believed to be caused by the impact of beta particles upon surrounding matter. Fig. 526 shows the effect of a powerful magnetic field on the complex Becquerel rays emitted from a small amount of radium. The heavy alpha particles are deflected slightly in one direction; the lighter beta particles are deflected more markedly in the other direction; the gamma rays are not deflected at all. By the use of such a magnetic field Rutherford learned the nature of the Becquerel rays.

**508. The Spinthariscope.** In 1903 Sir Wm. Crookes devised a little instrument called the *spinthariscope;* by the use of this instrument it may be shown that particles are being continually emitted from radium. A speck of

radium is mounted over a zinc sulphide screen. As the particles emitted by the radium strike the screen, they produce fluorescence. When the screen is examined in the dark by the use of a lens, a succession of sparks is seen. Each flash is produced by the impact of an alpha particle on the screen.

**509. Disintegration of the Atom.** Because heat and light appear to be given off continuously from radio-active substances without any apparent loss of weight, it was at first believed that radium is an exception to the law of the conservation of matter and energy. More careful investigations show that radium does slowly lose its energy. One half is lost in the first 1700 years, one half in the next 1700 years, and so on until its energy practically disappears. This expenditure of energy is entirely spontaneous; neither heat, light, cold, chemical action, nor electricity can be used to accelerate or to retard radio-activity.

The question naturally arises, "What is the source of all this energy?" A long series of experiments has furnished the answer to this question. The atoms of radium and other radio-active elements are exploding or disintegrating. The alpha and beta rays are products of atomic disintegration. Spontaneously certain atoms are breaking down into simpler and lighter atoms. Helium and niton, or radium emanation, are examples of atoms formed from radium. A little radium placed in a sealed tube soon produces these two elements. Radium emanation is now being very successfully used in the treatment of cancer. The heating effects are evidently due to the continual bombardment of the emitted particles, especially the alpha particles. The impact of these particles on air molecules ionizes them, or imparts to them an electric charge which renders them conductors. The rate at which an electroscope is discharged affords an accurate method for comparing the activity of radio-active substances. The old alchemists believed that it was possible to *transmute* one

element into another. Chemists have scoffed at their ideas of transmutation, only to learn recently that at least three elements undergo *spontaneous transmutation.*

**510. Can Atomic Energy be Utilized?** We have learned that one gram of good coal in burning yields about 8000 calories. It is possible to compute the amount of heat liberated by one gram of radium when disintegrating, if we know that it yields about 120 calories per hour throughout an average life of about 2500 years. The total amount is more than 300,000 times as much heat as can be obtained by burning an equal weight of coal. J. J. Thomson has estimated that the energy stored in one gram of hydrogen equals $6 \times 10^{11}$ foot pounds. This energy given off by one gram ($\frac{1}{453}$ lb.) of hydrogen would be sufficient to lift 10 battle-ships as big as the New Mexico, 32,000 tons each, to the top of Mt. Blanc, over $3\frac{1}{2}$ miles. Whether man will ever find a way to unlock this tremendous store of energy and put it to practical use is problematical. We have learned that the disintegration of the atom cannot be accelerated by any known chemical agency; radium is not affected by high temperatures nor by the greatest cold obtainable. It is reported that Rutherford succeeded recently in disintegrating the nitrogen atom by the action of radio-active substances themselves. This appears to be a step toward solving this interesting problem, but when we consider that he used as much radio-active energy to knock the atoms of nitrogen to pieces as he obtained from the disintegration, we find that the biggest part of the problem remains to be solved. Possibly atomic energy may at some future time replace coal and gasoline for fuel and power purposes; it is also possible that future generations may learn how to transmute lead and other base metals to gold; no one can foretell what the future may bring, especially when we consider the rapid strides that physics and chemistry have made during the last few decades.

## CHAPTER 29

# THE AUTOMOBILE

**511. Introductory.** The automobile is now so nearly omnipresent, and so many secondary school students are driving cars, that a text-book in physics is hardly complete if a study of this compound machine is neglected. Furthermore, a thorough understanding of the automobile furnishes students with a good working knowledge of physics. Nearly all of the fundamental principles of this science are used in the construction and operation of a modern automobile. For convenience, the automobile may be considered as consisting of three parts: (a) the power plant; (b) the chassis, or running gears; and (c) the body. In this chapter certain topics pertaining to the automobile which have not been discussed will be taken up first; then other parts of the automobile will be briefly reviewed.

**512. The Power Plant.** Some cars are made in which the steam engine is used successfully to furnish the motive power. A few cars are electrically driven by current furnished by storage batteries. Fig. 527 shows a phantom view of the rear axle of a motor truck which is driven by an electric motor. In the great majority of cars, however, the gasoline engine is used as the *driving* machine. Without the gas engine, the modern automobile would be practically impossible. But the gas engine has several defects which must be overcome by the use of additional mechanism. For example, the speed cannot be varied so easily as with the steam engine or electric motor. The gas engine cannot be reversed.

FIG. 527. — Axle driven by electric motor.

The single cylinder gasoline engine has only one power stroke in two complete revolutions. Greater flexibility is secured by the addition of more cylinders, so timed that the power strokes follow one another successively. Thus the number of cylinders has grown to two, four, six, eight, and even twelve. In a six cylinder engine the pistons are mounted on the crank-shaft in pairs oppositely placed. The angle between the pairs is 120°. The firing occurs successively; 1, 2, 3, 6, 5, 4, for example. Such a firing order gives smoothness, flexibility, and freedom from great vibration. Fig. 528 shows a sectional diagram of the six-cylinder engine of a car in common use.

**513. The Carburetor.** Contrary to the belief of many people, liquid gasoline does not explode. If the gasoline is vaporized, and its vapor is then mixed with the proper amount of air, an explosive mixture is formed. The carburetor is designed to vaporize gasoline and to mix it with the right amount of air before it enters the cylinders of the

FIG. 528. — Six-cylinder engine, sectional. The middle cylinders are cut away to show the position of the pistons. *A*, poppet valve, which is opened when the cam on cam-shaft *D* pushes up the push rod; *B*, spark plug; *C*, piston; *F*, fly-wheel; *G*, fan; *O*, oil reservoir; *P*, piston, sectional; *S*, crank-shaft bearing.

engine. There are many types of carburetors in use on different automobiles. By reference to Fig. 529, the operation may be better understood. As the gasoline enters the carburetor at *A*, it gradually lifts the float *F* until the levers *L* and *L′* close the valve *V*. The gasoline is vaporized as it flows through the spray nozzle *N* into the mixing chamber, where it is thoroughly mixed with air coming in through *B*. When the throttle *T* is opened the

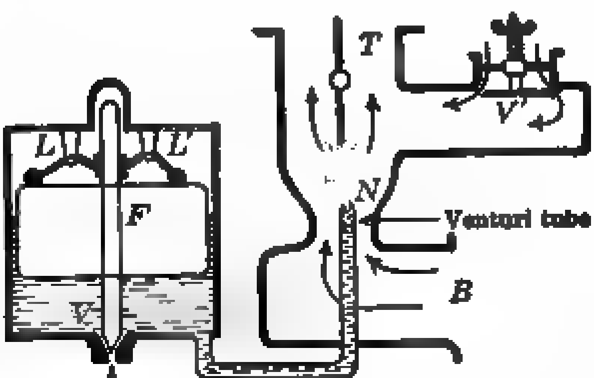


FIG. 529. — Diagram of carburetor.

explosive mixture is sucked into the engine. The venturi tube is narrowed at $N$ to give the air a higher velocity in this part of the tube. On account of this high velocity, the gasoline evaporates more rapidly.

An *ideal* carburetor would vaporize the gasoline perfectly and mix it with just enough air to burn *completely* every molecule of gasoline. Motorists know from experience that gasoline varies. For this reason it is not easy to have perfect adjustment for a carburetor to be used first with a gasoline mixture that needs 47 parts of air to one of vapor, and then with a gasoline mixture that needs 60 parts of air to one of gasoline. Furthermore, when a car is started, perfect vaporization is not secured until the engine warms up. For this reason a richer mixture must be used when starting. When the engine is running rapidly, the increased suction makes the evaporation of gasoline so rapid that more air must be introduced to make a "leaner" mixture. When the speed of the engine increases, the valve $V'$ opens automatically to admit auxiliary air.

FIG. 530. — Cone clutch diagram.

**514. The Clutch.** A gas engine will not start under load, since its working strokes are periodic. Therefore a clutch must be used to connect the engine or *driving* machine with the *driven* parts. One member of the clutch is attached to the crank-shaft of the engine just back of the fly-wheel, or in combination with it; the other member is attached to the transmission shaft. Several types of clutch are in use. One of the easiest to understand is the external cone clutch. In Fig. 530, $F$ shows the fly-wheel itself which is hollowed out to receive the conical surface of the *driven* member $M$.

As the operator pushes the foot lever *L* forward to disengage the clutch, the two members are separated and the fly-wheel revolves independently of the transmission system. When

FIG 531. — Multiple disc clutch and transmission gears. Note the use of ball bearings and roller bearings to reduce friction. The clutch and transmission are carefully housed to keep the parts free from dirt.

the pressure is released, a spring pushes *M* forward until it is in contact with the rotating fly-wheel. The surface of *M* is covered with leather or some friction material which

should slip some when pressure is first applied, and then hold firmly when the clutch is fully engaged. The clutch should be engaged gradually to avoid jerky operation and to bring the transmission units up to speed without too much strain.

The multiple disc clutch is quite extensively used. It consists of two sets of discs, one attached to the engine shaft, and the other to the transmission shaft. One set of discs is covered with some friction material. The disc clutch, Fig. 531, operates on the same principle as the cone clutch.

**515. The Transmission.** The speed at which a gas engine can be run may be varied to some extent by regulating the amount of gasoline, but such an engine is not very flexible. Then, too, the gas engine is not efficient when run at low speed. To enable the engine to run efficiently at high speed, and still permit the speed of the car itself to be varied, transmission gears are used on nearly all cars.

The transmission system consists of three shafts. Two of them, a pinion shaft *P* connected with the engine through the clutch, and the main drive shaft *D*, are on the same direct line, but they may turn independently of each other. The third shaft, *C*, which operates parallel to the others, is called a countershaft. The countershaft has four gears, all fixed on the shaft so they turn with it. The gear *A* of the pinion shaft is always in mesh with the gear *B* on the countershaft. The main drive shaft has two gears, *F* and *E*, which slide on the shaft, but always turn with it. Fig. 532 *A* shows the gears in neutral position. The pinion shaft and countershaft both turn in opposite directions, but they are not connected with the main driving shaft.

By means of a lever the operator may move the gear *E* forward until it is in mesh with the small gear *G* of the countershaft *C*. The gears are now in low speed position, and the power is transmitted as shown by the dotted line, Fig. 532 *B*.

The gears are shifted to "second," or intermediate speed by sliding the gear *F* backward until it is in mesh with gear

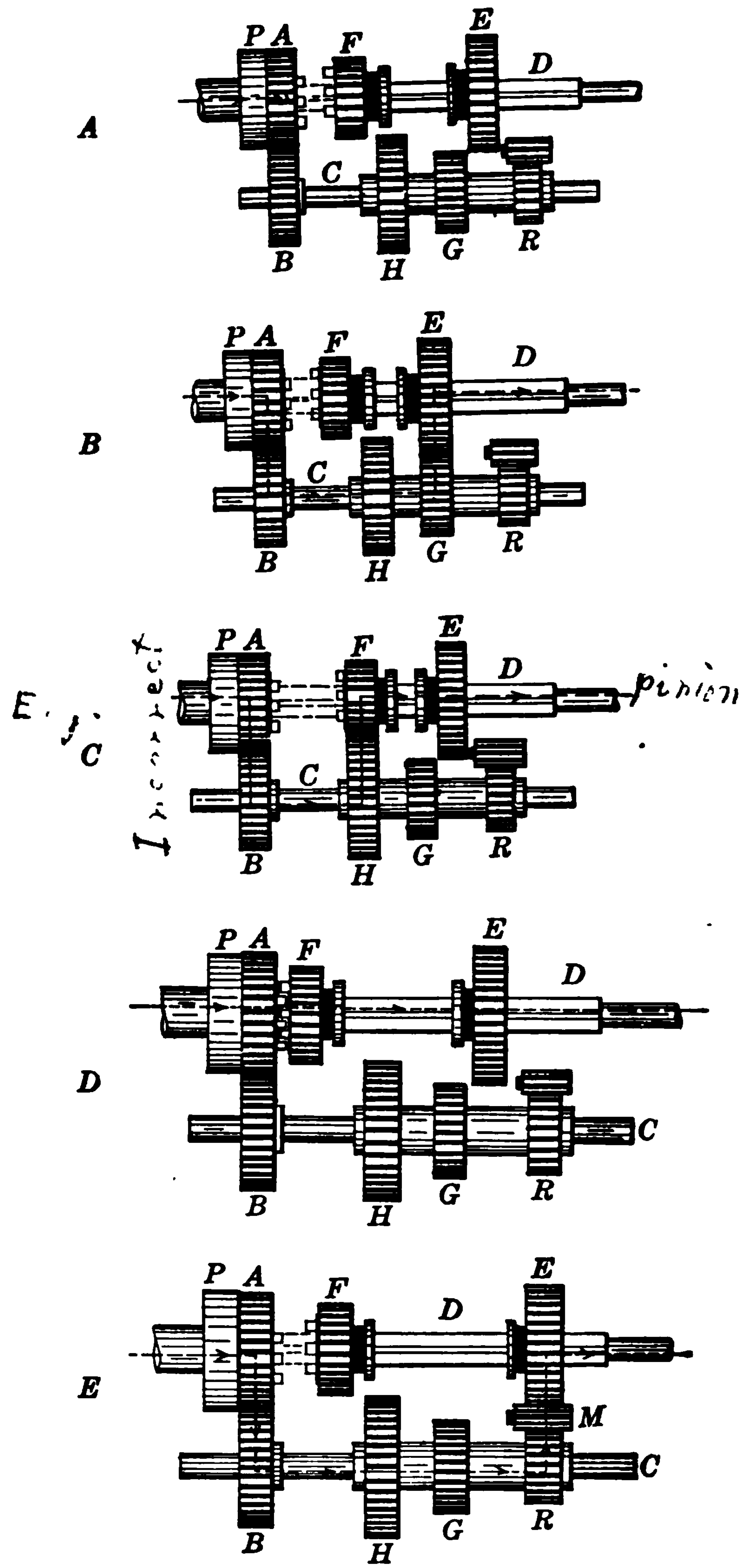



FIG. 532. — Transmission gears.

*H* on the countershaft. See Fig. 532 *C*. Note the dotted line, which shows power transmission.

In shifting to high speed position, the gear *F* is slid forward and locked by means of teeth to the pinion gear. Therefore on high speed the main shaft is locked to the pinion shaft and the drive is *direct* from the crank-shaft of the engine, Fig. 532 *D*.

To reverse the car the sliding gear *E* is moved back until it is in mesh with a small idler gear *M*. The number of gears in mesh is now odd, and the rear wheels are driven backward. See Fig. 532 *E*. The transmission system is connected with the differential on the

rear axles by means of double universal joints and a connecting drive shaft. Compare with transmission gear-set of Fig. 531.

**516. The Differential.** In rounding a corner the outer wheel of a car must travel faster than the inside wheel. The driving power of the engine is transmitted to the rear axles and it should be distributed equally to the two rear wheels. The engineer thus faces this problem. The two rear wheels must act together so the strain will be equally distributed between them, and yet they must be independent of each other for rounding curves. The solution is furnished by the differential, which is placed between the two parts of the divided rear axle. The driving pinion, *A*, Fig. 533, rotates the bevel gear *B*, which is rigidly attached to the frame *F*, and through the frame to the gears *C* and *E*. These parts must therefore rotate as a unit. The power is transmitted to the gears *D* and *G* from the differential gears *C* and *E*. On a straight road *D* and *G* travel at the same speed, and they also rotate with the main gear *B*. The gears *C* and *E* are not rotating on their axes, but they are carried around with the frame *F*. When the right axle turns faster than the left, then the gears *C* and *E* rotate on their axes in opposite directions. See also Fig. 538. If one wheel stops, the other rotates twice as fast. Fig. 534 shows a spur-gear differential used on one type of motor truck. Either wheel will drive.

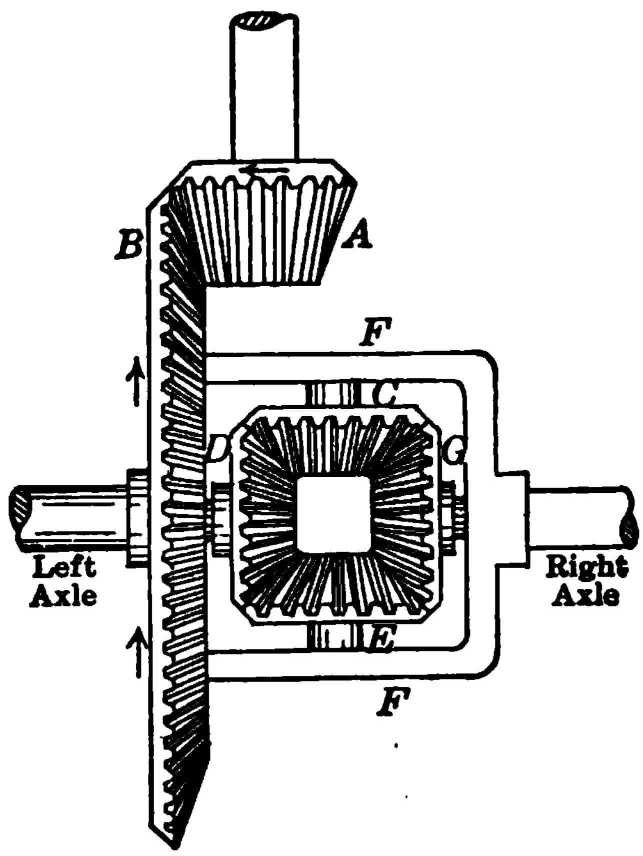


FIG. 533. — Differential diagram.

**517. The Ignition System.** In the operation of a gas engine, the spark must occur at just the proper time to ignite

FIG. 534. — Spur-gear differential. With this type of differential either wheel will drive. Note the speed reduction gears between the false and the true axle.

the explosive mixture. There are several ways of producing this spark. In the battery system, Fig. 535, storage cells are nearly always used, since they are more reliable than dry cells. An induction coil $I$ must be used to raise the voltage high enough to cause a spark to leap across the gap between the spark plug terminals, from $\frac{1}{32}$ to $\frac{1}{64}$ inch. Since the E.M.F. is highest at the break, an interrupter is used to break the circuit at exactly the right time. The rotation of the cam $A$ breaks the circuit four times during each revolution. (Four cylinder engine.) The interrupter $T$ is known as the *timer*. The condenser $C$ helps to fatten the spark.

In engines having more than one cylinder a distribution system must be used so the spark will occur successively in the different cylinders at just the right instant. In Fig. 535, the distributor $D$ is connected with the spark plugs of a four-cylinder engine. $F$ is a fiber ring made of some insulating material. The rotor $R$ is connected with one terminal of the secondary coil. As it rotates, the carbon brush which it carries makes contact in order with the metal segments set in the circumference of the fiber ring. Each segment is

connected to one terminal of a spark plug, the other terminal being grounded through the engine.

Both the interrupter and the distributor must be timed by gearing them with the engine. Generally both are set

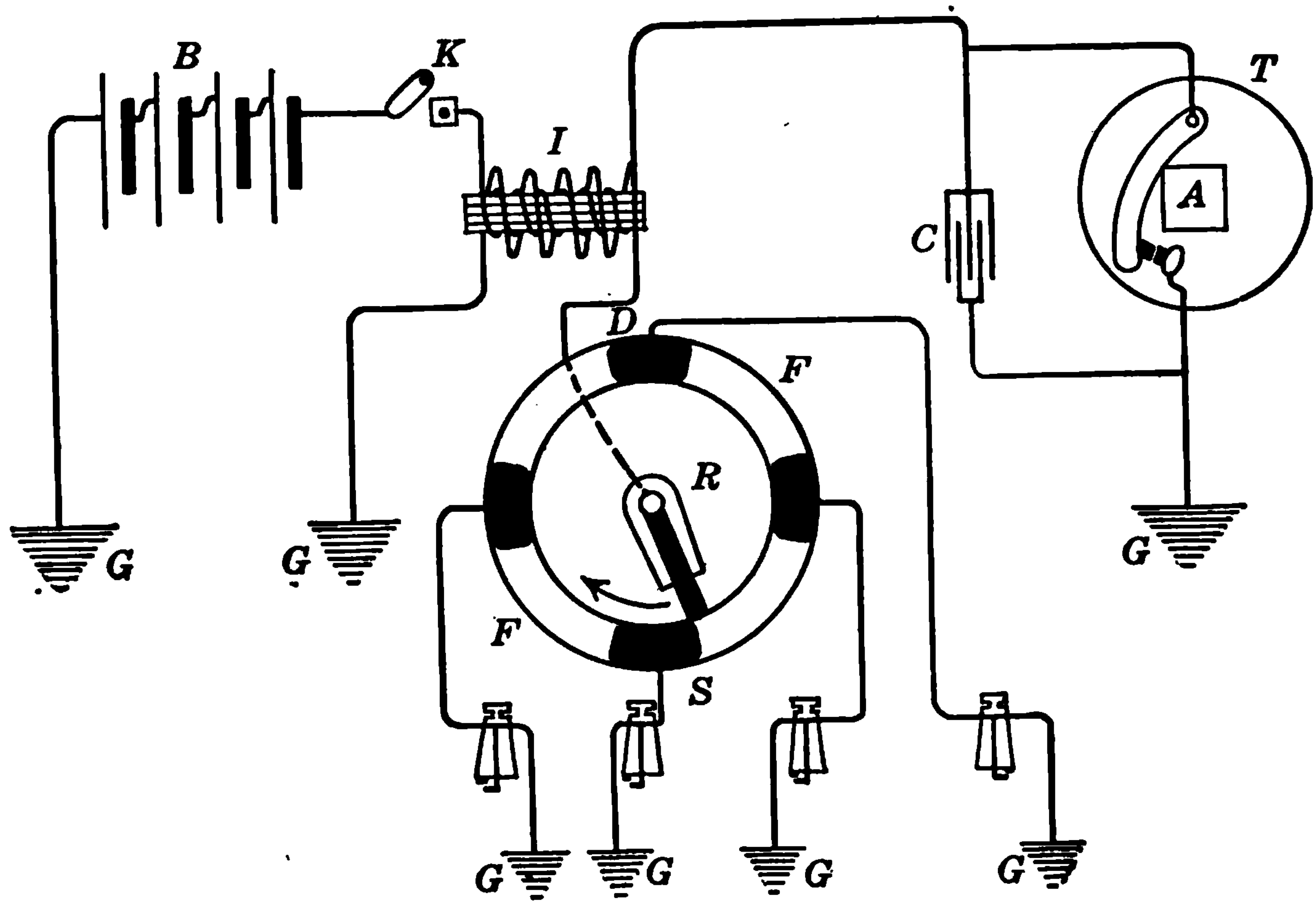



FIG. 535. — Simple ignition diagram.

on the same shaft. For a four-cycle engine, these parts are geared to rotate just half as fast as the crank-shaft, since an explosion occurs once in two revolutions.

The combustion of the gasoline mixture is not instantaneous. When the engine is running fast, the time required for the complete combustion may be so long comparatively that the burning gas does not expand completely before the power stroke is completed. This difficulty is met by advancing the spark a few degrees so the explosion will occur a little before the piston starts its working stroke. The spark is advanced by a lever which shifts the fiber ring so its segments are rotated in a direction opposite to that of the moving rotor. Moving the lever in the opposite direction retards the spark.

Some cars are operated on a low tension magneto system. With such a system a low voltage magneto takes the place of the batteries in the system just described. Sometimes battery ignition is used for starting, and a magneto is then used after the car is started.

High tension magnetos are also used for ignition. The secondary coil of such a magneto is wound upon the primary winding of the armature core. When the current is interrupted, there is induced in the secondary an E.M.F. of approximately 5000 volts, which is ample to produce the jump spark. The timer, condenser, and distributor are all grouped in the same housing.

**518. Review of Mechanics.** It will be interesting to review briefly our work in physics from the standpoint of the automobile and see how many principles and applications we can find exemplified.

Much attention must be paid to the properties of the materials of which a car is constructed. The men working in the automobile laboratories test such materials to determine their tenacity, malleability, elasticity, brittleness, and hardness. Chrome-vanadium steel is used for gear teeth and for springs in some cars; it is very hard and tough. The heavy fly-wheel used to keep the engine running smoothly is an example of the property of inertia. Too often motorists have demonstrated that two cars cannot occupy the same place at the same time. (Chap. 1.)

When we inflate the tires and note that the pressure is transmitted equally in all directions, we recall Pascal's law. To measure the air pressure within the tires a pressure gauge is used. The maker of the carburetor does not forget Archimedes when he makes the float to control the gasoline supply. A special hydrometer, Fig. 536, is used to test the specific weight of the electrolyte used in the storage battery. When the battery is fully charged, the specific weight of the acid rises to 1.280 or 1.300. As the battery runs down the

specific weight of the liquid falls, possibly to 1.15. The *freez-meter* is a modified form of hydrometer used to determine the freezing point of a mixture of alcohol and water used in automobile radiators. When the proportion of alcohol in the mixture is increased, both the specific weight and the freezing point are lowered. (Chap. 2.)

Wind resistance affords ample proof of air pressure, and a great deal of attention has been paid to the stream lines of the car body in an effort to decrease this resistance. To prevent the formation of a partial vacuum just behind a rapidly moving car, manufacturers now make racing cars with the rear pointed. The compressibility of gases and Boyle's law are applied in pumping up tires, and also during the compression stroke of the engine. Expansibility of gases and molecular motions are exemplified in the carburetor and in the cylinders of the engine. The impacts of the moving molecules furnish the driving force for the pistons. Pumps are represented by the compression pump for inflating tires, by the centrifugal pump sometimes used to keep the water circulating through the radiators, and by the oil pumps used for forcing oil to the bearings. In many cases a vacuum feed system is used to supply gasoline. (Chap. 3.)

FIG. 536. — Storage battery hydrometer.

In reviewing Chap. 4 we are reminded that moving molecules exert pressure in tires and cylinders. The carburetor furnishes an example of the evaporation of liquids and of the diffusion of vapors. Cohesion is important in the strength of materials, and the sticky varnish is an excellent example of adhesion. The steel used for the springs must have very

great resiliency, and the air in the tires is one of the best examples of perfect elasticity. The different kinds of oil used for lubricating light and heavy bearings afford an excellent study of the viscosity of liquids.

Without force applied to the pistons, no car could run. Parallel forces are applied to the steering wheel, furnishing an application of the couple. The student will be interested in searching for other examples of parallel forces, and for forces acting at an angle. Greater stability is secured by the use of an underslung chassis. A car of greater wheel-base rides more easily than a short car. Fig. 537 shows the balanced gears in a wheel of one type of motor truck. Much attention is also paid to the balancing of the crank-shaft in an effort to minimize vibration. (Chap. 5.)

Fig. 537. — Drive wheel with outer disc removed. Drive pinion is supported by teeth of two idler gears, giving efficiency of 97 %.

Cars are built for motion. A car starts with accelerated motion and the speed increases as the operator steps on the accelerator. In stopping a machine, the motion is retarded. The momentum of an automobile equals its mass times its velocity; heavy cars traveling at high velocity are not easily stopped. Too frequently a wrecked car at a curve bears mute testimony that the driver did not know that high

FIG. 538. — Full-floating rear axle and differential. The thrust roller bearings and brake bands are also shown. The foot, or service brake, acts on a flat, circular strip of steel lined with some friction material such as raybestos. When the brake lever is pressed, it pulls this band of steel tightly around a drum attached to the rear wheel, thus using friction to stop the car. The emergency brake lever expands a band of raybestos covered steel against the inner surface of the brake drum.

velocity and sharp curves both tend to increase centrifugal force. Efforts are made to increase friction in the clutch, by the use of non-skid tires, by the use of chains on tires, and in the brake linings. On the other hand, oil and grease are freely applied to the bearings to reduce friction. Fig. 538 shows a sectional view of a full-floating rear axle. The housing is cut away to show the differential and the bearings. Ball or roller bearings are used where possible, Fig. 539. (Chap. 6.)

FIG. 539. — Timken roller bearings.

The total force applied to the pistons equals the pressure of the exploding gas multiplied by the total area of all the pistons. To find the work done this product is multiplied by the length of the stroke, or force times distance. Now if we know the number of revolutions per second, we can find the horse power by the following formula:

$$\text{H.P.} = \frac{\text{pressure} \times \text{area} \times \text{length} \times \text{number}}{550 \times 2}.$$

The Society of Automobile Engineers uses the following simple formula to give the indicated horse power:

$$\text{H.P.} = \frac{D^2 N}{2.5}.$$

$N$ is the number of cylinders, and $D$ the diameter. (Chap. 7.)

The automobile is built of levers, screws, cams, and gears in endless number, and these simple machines all work in accord

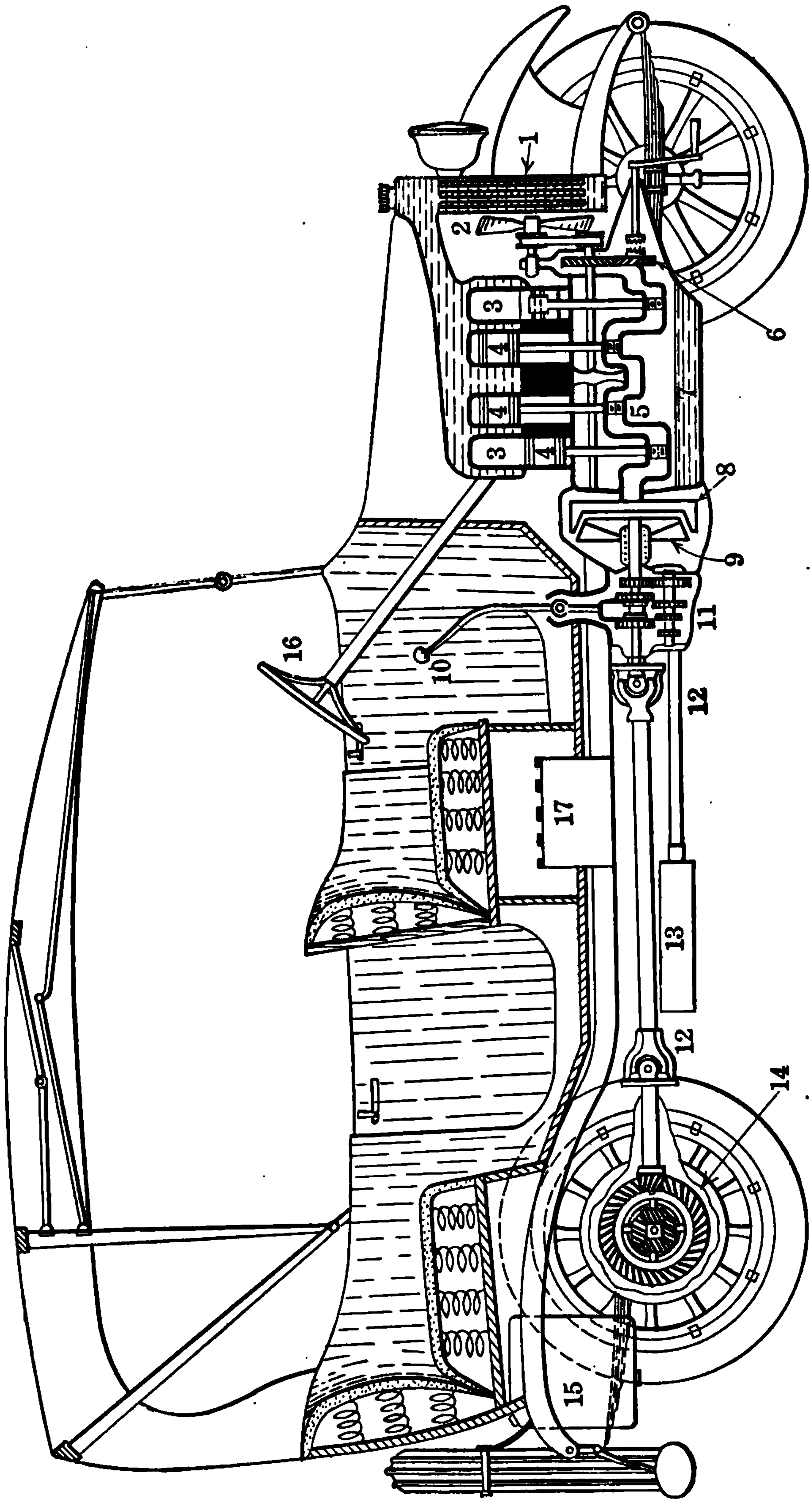



FIG. 540. — Diagram of car in profile. 1, radiator; 2, fan; 3, cylinders; 4, pistons; 5, crank-shaft; 6, timing gears; 7, oil reservoir; 8, fly-wheel; 9, clutch; 10, gear-shift lever; 11, transmission gears; 12, universal joint; 13, muffler; 14, differential; 15, gasoline tank; 16, steering wheel; 17, battery.

with the general law of machines which we learned in Chap. 8. The full-page diagram of a car in profile furnishes the student with an idea of the manner in which many simple machines articulate to make a big compound machine, Fig. 540. To illustrate, the steering wheel acts on a worm gear which transmits the applied force to the steering knuckle. The front spindle upon which the wheel turns forms one arm of a bent lever steering knuckle, which is pivoted to the front axle by means of a king bolt. One type of worm drive is shown in Fig. 541.

Fig. 541. — Worm drive motor truck.

**519. Review of Heat.** When a car is driven some distance the temperature of the air inside the tires increases. The same thing occurs when tires stand in the sun. Heating these gases causes increased pressure, since the hot gases are not permitted to expand in accord with the law of Charles. The heat from the exploding gases causes great expansion and furnishes the driving force for the engine. (Chaps. 9 and 10.) The expansion of overheated bearings may burn them out and destroy them, if friction is not reduced by proper lubrication.

The constant series of explosions would soon heat the cylinders red hot, if cooling systems were not used. An engine works better when it is hot, but too great heat would cause the cylinders to become distorted, and the gasoline mixture would be prematurely ignited by the hot cylinders themselves. Motor-cycle engines and the engines of some cars are air-cooled. In such cases the outside surface of the cylinders is made irregular to increase the amount

of surface exposed to the cooling air currents. Fig. 542 shows the surfaces of the cylinders and the method used to circulate the air around the cylinders of an air-cooled car. The engines of most cars are water-jacketed. The water, which has a high thermal capacity, absorbs heat from the cylinders and then flows to the radiator, where it loses this heat to the air, which is sucked through the radiator by means of a rapidly

FIG. 542. — Engine is air-cooled. Fan distributes air.

rotating fan. In the Thermo-Syphon system of cooling, the water circulates through the radiator by convection. The metal walls are warmed by conduction, and the heat is lost to the air by radiation. Often pumps are used to keep the water circulating freely. If the water freezes in cold weather, a cracked radiator or water-jacket furnishes convincing proof of the expansion of freezing water. Several anti-freezing mixtures are in use. Such salts as calcium chloride when dissolved in water lower the freezing point, but salts

dissolved in water are apt to cause corrosion of the radiator, or to deposit scale. A mixture of denatured alcohol and water is not corrosive. When 30% of alcohol and 70% of water are used, the mixture freezes at $-1°$ F. But alcohol evaporates faster than water and the freezing point of the mixture gradually rises as a result of such fractional distillation. Glycerine, denatured alcohol, and water are sometimes used, since glycerine retards the evaporation of alcohol. For example, 15% glycerine, 15% alcohol, and 70% water form a more permanent mixture which freezes at $-5°$ F. (Chaps. 11 and 12.)

Some cars use a steam engine instead of the gas engine. Oil or gasoline is the fuel used; the boiler consists of a long coiled pipe to which the water is delivered at one end and converted into superheated steam at high pressure as it passes through the long coil. A water pump keeps the boiler supplied with water. The student should review the gas engine and its mechanism as discussed in Chap. 13.

**520. Review of Sound.** Unfortunately, machinery seldom runs without vibration, and we know that vibrations set up sound waves. Novelists often speak of a purring motor. It is true that a well-oiled motor may run smoothly enough to yield a musical note, but very often irregular vibrations which result in discordant notes are produced by the motor or the gears. Motorists sometimes locate "knocks" in the engine by holding one end of a screw driver against the cylinder and then resting the side of the head upon the other end of the screw driver. By setting the teeth at an angle in spiral or helical gears, efforts are made to reduce noises. The poppet valves are bound to be noisy. Sleeve valves which slide in the cylinders between the piston and the cylinder walls are used in one type of car in an effort to reduce noise and vibration. A rotary valve is now made which promises to be successful. A cylinder about $2\frac{1}{2}$ in. in diameter rotates in the cylinder head, opening and closing the

gas ports alternately. A muffler, Fig. 543, is used to deaden the noise from the exhaust of the engine. The muffler lowers the efficiency of the car slightly more than 1%, hence motorists sometimes cut out the muffler and let the exhaust gases escape directly into the air. Anti-noise ordinances forbid the use of the noisy cut-out in most cities. On the other hand, noise is sometimes desirable as a warning to pedestrians and the drivers of other vehicles. A siren is sometimes used to give a more musical note than the "honk" of the ordinary horn or klaxon. (Chaps. 14 and 15.)

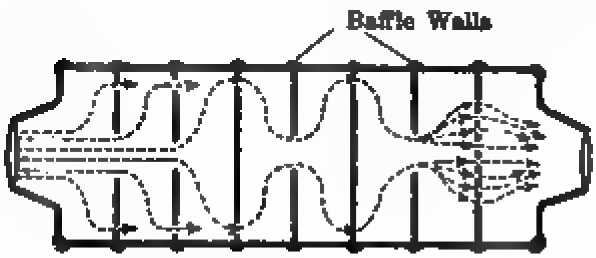



FIG. 543. — Muffler. Exhaust gases take circuitous path.

**521. Review of Light.** Cars are now lighted almost exclusively by electricity. To enable the driver to see vehicles approaching from the rear, a small convex mirror is used. To light the roadway in front at night, concave mirrors are used in the headlight as reflectors. The light is placed just a trifle nearer the mirror than its focal length, so the reflected rays are only slightly divergent. The same type of mirror is used in the search-light sometimes used by drivers. Anti-glare lenses must be used to diffuse these intense lights and thus prevent the blinding of persons approaching the car. Fig. 544. (Chaps. 16, 17, and 18.)

The color of the car was an important item during the World War. Certain colors, such as gray and khaki, blend with the landscape and give "low visibility." Various combinations were used to deceive the enemy, and camouflage became an art in itself. The red tail-light

FIG. 544. — Anti-glare lens.

is always displayed at night as a danger signal. (Chap. 20.)

**522. Review of Electricity.** In our study of the ignition systems of automobiles, we learned how the magneto and the induction coil are used with the timer to produce an electric spark at just the proper instant. The magneto uses permanent magnets to set up a magnetic field which is cut by the rotating coils of the armature to produce an induced current. In the Ford magneto there are 16 station-


FIG. 545. — In this magneto the magnets rotate with the fly-wheel. The disc carrying the coils is stationary.

ary coils. Sixteen permanent magnets are fastened to the fly-wheel of the engine and thus revolve with it. Fig. 545. To increase the length of the spark the E.M.F. is raised by means of the induction coil. The spark is fattened by the condenser. The fiber ring and the metal segments which it bears furnish us with a contrast between conductors and insulators. The dry cells which were at one time extensively used for ignition have now yielded to the storage battery.

To operate the lighting system the storage battery is used. Generally three or four cells are connected in series, giving a pressure of from 6 to 8 volts. Sometimes it is necessary to have the battery charged, but if the car is run on a fairly long trip occasionally, the battery will be kept fully charged by a generator operated by the engine. The generator is a small direct-current dynamo. When the engine runs slowly the coils of the armature do not cut lines of

force fast enough to furnish the voltage needed for charging the battery. An underload circuit breaker is used to disconnect the batteries when the car is running slowly. Then the battery does not discharge back through the generator. At higher speeds, 10 miles or more per hour, the generator is charging the battery. When a car is driven at a very high speed, the battery is again automatically cut out of the charging circuits.

The self-starter consists of a motor geared in mesh with the crank shaft of the engine. The motor is operated by current from the storage battery. A series-wound motor is always used because it has a large starting torque; shunt motors do not start under load. Short trips with frequent use of the self-starter discharge the battery quite rapidly. Dials on the dash show whether the battery is charging or discharging. An ammeter forms part of the electrical equipment.

The electric lights furnish examples of the heating effects of the electric current. The wiring circuits are protected with fuses or with automatic circuit breakers. Some luxurious cars are artificially heated by electricity. The magnetic effects of the electric current are exemplified by the generator and motor, and the chemical effects in the charging of the storage cells. With its magnets, conductors, cells, measuring instruments, motor, generator, lights, and spark coils, the modern automobile utilizes nearly every principle of magnetism and electricity.

## QUESTIONS

1. Refer to Fig. 540 and pick out as many simple machines as possible.

2. Is a wheel a lever? Explain.

3. With the ordinary differential, is a chain on only one rear wheel a help in starting a car on slippery streets?

LOSSES BY PERCENTAGE.

COOLING WATER 35.8 %

EXHAUST GASES 36.6 %

EXHAUST PIPES 1.0 %

MUFFLER 1.2 %

ENGINE FRICTION 5.6 %

TRANSMISSION FRICTION 2 9 %

REAR TIRES 3.7 %

FRONT TIRES 1.1 %

FRONT WHEELS 0.6 %

AIR RESISTANCE 7.1 %

FIG. 546. — Diagram shows dispersion of energy from fuel by a high-class touring car traveling at a speed of 40 miles per hour. (Courtesy of Tide Water Oil Co.)

4. Why does increasing the number of cylinders give greater flexibility to a gas engine?

5. Why is it necessary to bring a car to a full stop before shifting to reverse gear?

6. Why is it economical to drive a car at a moderately high speed, but wasteful to drive at a very high speed?

7. It is impossible to start a car if the cylinders are "flooded," or full of gasoline vapor. Explain.

8. If the maximum retardation of the brakes is 10 ft. per sec., can a driver stop a car traveling 30 mi. per hr. within 100 ft. ($v = \sqrt{2aS}$)?

9. What is the effect of "advancing" or "retarding" the spark?

10. Is the energy in gasoline kinetic or potential? Discuss the transformations of energy involved in starting and running an automobile. See the energy diagram of Fig. 546.

11. Show how "inflating a tire" exemplifies: (*a*) heat by friction and compression (internal friction); (*b*) molecular motion; (*c*) law of Boyle; (*d*) Pascal's law.

# APPENDIX A

## FORMULAS

1. *Density.*

$$D = \frac{W}{V}.$$

$D$ is density; $W$, weight; and $V$, volume.

2. *Liquid Pressure.*

$$P = hd.$$

$P$ is pressure; $h$, the depth of the liquid; and $d$, the density.

3. *Total Force.*

$$F = ahd.$$

$a$ is the area of the surface; $h$, depth of liquid; and $d$, the density.

4. *Boyle's Law.*

$$VP = V'P'.$$

$V$ is original volume; $P$, original pressure; $V'$, new volume; and $P'$, new pressure.

5. *Accelerated Motion.*

$$V = at, \text{ or } V = gt.$$

$V$ is velocity at end of any given second; $t$, time; $a$, acceleration; and $g$, acceleration when body is freely falling.

6. *Accelerated Motion.*

$$S = \tfrac{1}{2}at^2, \text{ or } S = \tfrac{1}{2}gt^2.$$

$S$ is distance for any given number of seconds; $t$, time; $a$, acceleration; and $g$, acceleration due to gravity.

7. *Accelerated Motion.*

$$S' = \tfrac{1}{2}a(2t-1), \text{ or } S' = \tfrac{1}{2}g(2t-1).$$

$S'$ is the distance the body moves in any *given* second; $t$, time; $a$, acceleration; and $g$, acceleration when body is freely falling.

8. *Accelerated Motion.*

$$V = \sqrt{2aS}, \text{ or } V = \sqrt{2gS}.$$

$V$ is velocity at end of any given second; $S$, distance; $a$, acceleration; and $g$, acceleration due to gravity.

9. *Pendulum. Law of Lengths.*

$$t : t' = \sqrt{l} : \sqrt{l'}.$$

$t$ and $t'$ represent the time of vibration; $l$ and $l'$ represent the lengths of the pendulums.

10. *Pendulum.*

$$t = \pi\sqrt{\frac{l}{g}}.$$

$t$ represents time; $l$, length of pendulum; and $g$, acceleration due to gravity.

11. *Centrifugal Force.*

$$\text{C.F.} = \frac{mv^2}{gr}.$$

If $m$ represents mass in grams, $v$, velocity in centimeters, $r$, radius in cm., and $g$, acceleration due to gravity, then C.F. equals the centrifugal force in grams.

When $m = \text{lb.}$, $v$ and $r$, ft., then C.F. equals centrifugal force in pounds.

12. *Work.*

$$W = Fs.$$

$W$ represents work done; $F$, acting force; and $s$, the distance the force acts.

13. *Power.*

$$\text{H.P.} = \frac{Fs}{550t}.$$

If $F$ represents force in pounds, $s$, distance in feet, and $t$ the time in seconds, then H.P. represents horse power.

14. *Potential Energy.*

$$\text{P.E. (in gravitational units)} = mh.$$

$m$ is mass and $h$ the distance.

$$\text{P.E. (in ergs)} = mgh.$$

15. *Kinetic Energy.*

$$\text{K.E. (in ergs)} = \tfrac{1}{2}mv^2.$$

$m$ is mass in gm., and $v$ the velocity in centimeters.

16. *Work Principle.*

$$E \times d = R \times d'.$$

$E$ is effort; $d$, distance effort moves; $R$, resistance; and $d'$, distance resistance moves.

17. *Lever.*

$$\text{M.A.} = \frac{EF}{RF}.$$

$EF$ is length of effort arm and $RF$ the length of the resistance arm. *M.A.* is mechanical advantage of force; the advantage of speed in machines is always the inverse ratio of the mechanical advantage of force.

18. *Pulley.*

$$En = R.$$

$E$ is effort; $R$, the resistance; and $n$, the number of strands supporting the movable block.

19. *Wheel and Axle.*

$$\text{M.A.} = \frac{C}{c} \text{ or } \frac{D}{d} \text{ or } \frac{R}{r}.$$

$C$, $D$, and $R$ represent respectively the circumference, diameter, or radius of the wheel; $c$, $d$, and $r$ represent respectively the circumference, diameter, or radius of the axle.

20. *Inclined Plane.*

$$\text{M.A.} = \frac{l}{h}.$$

$l$ represents the length of the plane and $h$ the height. (Force is applied parallel to plane.)

$$\text{M.A.} = \frac{b}{h}.$$

When force is applied parallel to the base of the plane, then $b$ represents the base and $h$ the height.

21. *Screw.*

$$\text{M.A.} = \frac{2\pi r}{d}.$$

$r$ is radius of lever upon which the effort acts, and $d$ is the interval or distance between the threads of the screw.

22. *Centigrade and Fahrenheit Scales.*

$$\frac{C}{F-32} = \frac{5}{9}.$$

$C$ and $F$ represent Centigrade and Fahrenheit thermometer readings.

23. *Laws of Boyle and Charles.*

$$\frac{PV}{T} = \frac{P'V'}{T'}.$$

$P$, $V$, and $T$ represent original pressure, volume, and absolute temperature; $P'$, $V'$, and $T'$ represent new pressure, volume, and absolute temperature.

24. *Coefficient of Linear Expansion.*

$$K = \frac{l'-l}{l(t'-t)}.$$

$l$ represents the length before expansion; $l'$, the length after expansion; $t$, the original temperature; and $t'$, the final temperature.

25. *Heat Exchange.*

$$mst = m's't'.$$

$m$, $s$, and $t$ represent the mass, specific heat, and change of temperature in Centigrade degrees of substance losing heat;

$m'$, $s'$, and $t'$ represent the mass, specific heat, and change of temperature of substance gaining heat.

26. *Wave Length.*

$$v = nl.$$

$v$ is velocity of sound; $n$, the number of vibrations per second; and $l$, the wave length.

27. *Size of Object and Image.*

$$S_o : S_i = D_o : D_i.$$

$S_o$ and $S_i$ represent the size of object and image respectively; $D_o$ and $D_i$ represent the distances of object and image from the centèr of curvatüre.

28. *Lens Formula.*

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F}.$$

$D_o$ is the object's distance; $D_i$, the image distance; and $F$, the focal length.

29. *Ohm's Law.*

$$I = \frac{E}{R}, \text{ or } I = \frac{V}{R}, \text{ or } I = \frac{P.D.}{R}.$$

$I$ is the strength of current in amperes; $R$, the resistance in ohms; $E$, the electromotive force; $V$, the voltage; and $P.D.$, the potential difference.

30. *Resistance.*

$$R = \frac{Kl}{d^2}.$$

$K$ is a constant dependent upon the material; $l$ is the length in feet; and $d$ is the diameter of the conductor in mils, or thousandths of an inch.

31. *Cell Formula.*

$$I = \frac{E}{r+R}.$$

$I$ is the strength of the current; $E$, the voltage; $r$, the internal resistance of the cell; and $R$, the external resistance.

32. *Series Grouping.*

$$I=\frac{nE}{nr+R}.$$

$I$ is the strength of the current; $E$, the voltage; $r$, the internal resistance of a single cell; $R$, the total external resistance; and $n$, the number of cells.

33. *Parallel Grouping.*

$$I=\frac{E}{\frac{r}{n}+R}.$$

The letters have the same significance as in No. 32.

34. *Electric Heating.*

$$\text{Calories}=I^2R\times t\times 0.24.$$

$I$ is the strength of the current in amperes; $R$, the resistance; and $t$, the time in seconds.

35. *Shunt Resistance.*

$$\frac{1}{R}=\frac{1}{r}+\frac{1}{r'},\text{ or }R=\frac{rr'}{r+r'}.$$

$R$ represents total resistance; $r$, the resistance of one branch of the shunt; and $r'$ the resistance of the other branch.

# APPENDIX B

## TABLE 1. — USEFUL NUMBERS

| | | | |
|---|---|---|---|
| 12 in. | = 1 ft. | 3 ft. | = 1 yd. |
| $16\frac{1}{2}$ ft. | = 1 rd. | 320 rd. | = 1 mi. |
| 5280 ft. | = 1 mi. | 144 sq. in. | = 1 sq. ft. |
| 9 sq. ft. | = 1 sq. yd. | 1728 cu. in. | = 1 cu. ft. |
| 27 cu. ft. | = 1 cu. yd. | 2150.4 cu. in. | = 1 bu. |
| 231 cu. in. | = 1 gal. | 60 mi. per hr. | = 88 ft. per sec. |
| 1 lb. avoir. | = 7000 gr. | 1 lb. Troy | = 5760 gr. |
| 1 oz. avoir. | = 437.5 gr. | 1 oz. Troy | = 480 gr. |
| 1 cu. ft. of water weighs 62.4 lb. | | $\pi^2$ | = 9.86965. |
| Circumference of a circle | $= 2\pi r$ | Area of circle | $= \pi r^2$, or $\frac{1}{4}\pi d^2$ |
| Surface of sphere | $= 4\pi r^2$ | Volume of sphere | $= \frac{1}{6}\pi d^3$ |

## TABLE 2. — METRIC-ENGLISH EQUIVALENTS

| | | | |
|---|---|---|---|
| 1 in. | = 2.5399 cm. | 1 ft. | = 30.479 cm. |
| 1 mi. | = 1609.3 m. | 1 mi. | = 1.6093 Km. |
| 1 mm. | = .03937 in. | 1 cm. | = .3937 in. |
| 1 m. | = 39.3708 in. | 1 m. | = 3.2809 ft. |
| 1 m. | = 1.0936 yd. | 1 sq. cm. | = 0.155 sq. in. |
| 1 sq. in. | = 6.451 sq. cm. | 1 cu. in. | = 16.3862 c. c. |
| 1 lb. | = 453.593 gm. | 1 Kgm. | = 2.2046 lb. |
| 1 oz. | = 28.3495 gm. | 1 gm. | = 15.432 gr. |

## TABLE 3. — SPECIFIC WEIGHT OF SOLIDS

| | | | |
|---|---|---|---|
| Aluminum | 2.7 | Coal, bituminous | 1.26–1.4 |
| Antimony | 6.72 | Copper | 8.9 |
| Beeswax | 0.96 | Cork | 0.24 |
| Brass | 8.2–8.7 | Diamond | 3.53 |
| Brick | 1.6–2.0 | Elm | 0.58 |
| Bronze | 8.7 | Glass, crown | 2.5 |
| Butter | 0.94 | Glass, flint | 3.0–3.6 |
| Carbon | 1.7–3.5 | Gold | 19.3 |
| Chestnut | 0.61 | Gold, 18k. | 14.88 |
| Cherry | 0.71 | Granite | 2.65 |
| Coal, anthracite | 1.26–1.8 | Graphite | 2.50 |

TABLE 3. — *Continued*

| | | | |
|---|---|---|---|
| Human Body | 1.07 | Paraffin | 0.824–0.94 |
| Ice | 0.917 | Pine | 0.46–0.55 |
| Iron, cast | 7.1–7.6 | Platinum | 21.4 |
| Iron, steel | 7.79 | Porcelain | 2.38 |
| Iron, wrought | 7.8–7.9 | Quartz | 2.65 |
| Lead | 11.34 | Silver | 10.5 |
| Lignum vitae | 1.33 | Silver, sterling | 10.38 |
| Limestone | 3.18 | Sulphur | 2.0 |
| Maple | 0.755 | Tallow | 0.94 |
| Magnesium | 1.74 | Tin | 7.0–7.3 |
| Marble | 2.7 | Tungsten | 18.7 |
| Oak | 0.85 | Zinc | 7.1 |

TABLE 4. — SPECIFIC WEIGHT OF LIQUIDS

| | | | |
|---|---|---|---|
| Alcohol, grain | 0.794 | Mercury | 13.56 |
| Alcohol, wood | 0.804 | Milk | 1.029 |
| Carbon bisulphide | 1.27 | Nitric acid, 68% | 1.41 |
| Carbon tetrachloride | 1.60 | Oil, castor | 0.963 |
| Chloroform | 1.50 | Oil, cottonseed | 0.924 |
| Ether | 0.72 | Oil, linseed | 0.94 |
| Gasoline | 0.68–0.71 | Oil, olive | 0.916 |
| Glycerin | 1.26 | Turpentine | 0.87 |
| Hydrochloric acid | 1.20 | Sulphuric acid | 1.84 |
| Kerosene | 0.778–0.804 | Water, sea | 1.026 |

TABLE 5. — CAPACITY OF AIR IN GRAINS OF WATER VAPOR PER CUBIC FOOT

| Degrees F. | Grains per Cubic Foot | Degrees F. | Grains per Cubic Foot | Degrees F. | Grains per Cubic Foot | Degrees F. | Grains per Cubic Foot |
|---|---|---|---|---|---|---|---|
| 10 | .776 | 46 | 3.539 | 66 | 7.009 | 86 | 13.127 |
| 20 | 1.235 | 48 | 3.800 | 68 | 7.480 | 88 | 13.937 |
| 30 | 1.935 | 50 | 4.076 | 70 | 7.980 | 90 | 14.790 |
| 32 | 2.113 | 52 | 4.372 | 72 | 8.508 | 92 | 15.689 |
| 34 | 2.279 | 54 | 4.685 | 74 | 9.066 | 94 | 16.634 |
| 36 | 2.457 | 56 | 5.016 | 76 | 9.655 | 96 | 17.626 |
| 38 | 2.646 | 58 | 5.370 | 78 | 10.277 | 98 | 18.671 |
| 40 | 2.849 | 60 | 5.745 | 80 | 10.934 | 100 | 19.766 |
| 42 | 3.064 | 62 | 6.142 | 82 | 11.626 | 102 | 20.917 |
| 44 | 3.294 | 64 | 6.563 | 84 | 12.356 | 104 | 22.125 |

TABLE 6. — HEAT CONSTANTS

| Name | Specific Heat | Melting Point | Boiling Point | Heat of Fusion | Heat of Vaporization |
|---|---|---|---|---|---|
| Alcohol . . | .65 | −130° C. | 78° C | | 205 |
| Aluminum . | .217 | 657 | 2200 | 76.8 | |
| Ammonia . | | −75 | −33.5 | 108 | 295 |
| Brass . . . | .09 | 912 | | | |
| Copper . . | .093 | 1065 | 2310 | 42 | |
| Glass . . . | .198 | | | | |
| Ice . . . . | .5 | 0 | | 80 | |
| Iron . . . | .113 | 1550 | 2450 | 28 | |
| Lead . . . | .031 | 327 | 1525 | 5.8 | |
| Mercury . . | .033 | −39 | 357 | 2.8 | |
| Platinum . | .0323 | 1760 | | 27.2 | |
| Silver . . . | .056 | 961 | 1952 | 21. | |
| Tungsten . | .0336 | 3000 | | | |
| Steam . . | .48 | | | | |
| Water . . | 1.00 | | 100 | | 536 |
| Zinc . . . | .093 | 419 | 918 | 28 | |

TABLE 7. — TENSILE STRENGTH

| Material | Pounds per Square Inch | Material | Pounds per Square Inch |
|---|---|---|---|
| Aluminum . . | 30,030–40,000 | Iron, piano wire | 357,000–390,000 |
| Brass . . . . | 50,000–150,000 | Lead, drawn . | 2600–3300 |
| Bronze wire | | Platinum, drawn | 50,000 |
| phosphor . . | 110,000–140,000 | Silver, drawn . | 42,000 |
| Copper, drawn . | 60,000–70,000 | Steel, ordinary . | 80,000–330,000 |
| Iron, annealed . | 50,000–60,000 | Steel, maximum | 460,000 |
| Iron, hard drawn | 80,000–120,000 | | |

## TABLE 8. — VELOCITY OF SOUND IN VARIOUS MEDIA. (APPROXIMATE)

| Material | Feet per Second | Material | Feet per Second |
|---|---|---|---|
| Air | 1,089 | Iron | 16,500 |
| Aluminum | 16,750 | Steel | 16,500 |
| Brass | 11,500 | Water, 4° C. | 4,590 |
| Copper | 12,000 | Water, 15° C. | 4,615 |
| Glass | 16,500 | Wood, along grain | 14,300 |
| Hydrogen | 4,163 | Wood, across grain | 12,600 |

## TABLE 9. — VAPOR PRESSURE OF WATER IN MILLIMETERS OF MERCURY

| Degrees C. | Millimeters | Degrees C. | Millimeters | Degrees C. | Millimeters |
|---|---|---|---|---|---|
| 0 | 4.5 | 23 | 20.9 | 60 | 148.9 |
| 5 | 6.5 | 24 | 22.2 | 70 | 233.3 |
| 10 | 9.1 | 25 | 23.5 | 80 | 354.7 |
| 15 | 12.7 | 26 | 25.0 | 85 | 433.1 |
| 16 | 13.5 | 27 | 26.5 | 90 | 525.4 |
| 17 | 14.4 | 28 | 28.1 | 95 | 633.7 |
| 18 | 15.3 | 29 | 29.8 | 96 | 657.7 |
| 19 | 16.3 | 30 | 31.5 | 97 | 682.1 |
| 20 | 17.3 | 35 | 41.6 | 98 | 707.3 |
| 21 | 18.5 | 40 | 54.8 | 99 | 733.2 |
| 22 | 19.6 | 50 | 92.0 | 100 | 760. |

## TABLE 10.—DENSITY OF WATER AT VARYING TEMPERATURES

| Degrees C. | Grams per Cubic Centimeter | Degrees C. | Grams per Cubic Centimeter | Degrees C. | Grams per Cubic Centimeter |
|---|---|---|---|---|---|
| 0 | .99987 | 15 | .99913 | 60 | .98324 |
| 1 | .99993 | 20 | .99823 | 65 | .98059 |
| 2 | .99997 | 25 | .99708 | 70 | .97781 |
| 3 | .99999 | 30 | .99568 | 75 | .97489 |
| 4 | 1.00000 | 35 | .99406 | 80 | .97183 |
| 5 | .99999 | 40 | .99225 | 85 | .96865 |
| 6 | .99998 | 45 | .99025 | 90 | .96534 |
| 8 | .99987 | 50 | .98807 | 95 | .96192 |
| 10 | .99973 | 55 | .98573 | 100 | .95838 |

## TABLE 11.—RELATIVE CONDUCTIVITY OF HEAT

| | | | | | |
|---|---|---|---|---|---|
| Silver | 100 | German silver | 7–8 | Magnesia | .016 |
| Copper | 92 | Mercury | 1.6 | Paper | .013 |
| Aluminum | 48 | Concrete | .22 | Sawdust | .012 |
| Zinc | 27 | Glass | .11–.23 | Wool | .010 |
| Brass | 21–28 | Sand, white | .09 | Silk | .0095 |
| Platinum | 17 | Asbestos | .04 | Felt | .0087 |
| Iron | 12–15 | Soil, dry | .033 | Air | .005 |
| Steel | 6–11.7 | Firebrick | .028 | Cotton wool | .0043 |
| Lead | 8 | Linen | .021 | | |

TABLE 12.—PROPERTIES OF COPPER WIRE

| Gauge Number | Diameter, mils | Ohms per 1000 Feet at 0° C. | Ohms per 1000 Feet at 20° C. | Feet per Ohm 20° C. |
|---|---|---|---|---|
| 0000 | 460 | .04516 | .04901 | 20,400 |
| 000 | 409.6 | .05695 | .06180 | 16,180 |
| 00 | 364.8 | .07181 | .07793 | 12,830 |
| 0 | 324.9 | .09055 | .09827 | 10,180 |
| 1 | 289.3 | .1142 | .1239 | 8,070 |
| 2 | 257.6 | .1440 | .1563 | 6,400 |
| 3 | 229.4 | .1816 | .1970 | 5,075 |
| 4 | 204.3 | .2289 | .2485 | 4,025 |
| 5 | 181.9 | .2887 | .3133 | 3,192 |
| 6 | 162.0 | .3640 | .3951 | 2,531 |
| 7 | 144.3 | .4590 | .4982 | 2,007 |
| 8 | 128.5 | .5988 | .6282 | 1,592 |
| 9 | 114.4 | .7299 | .7921 | 1,262 |
| 10 | 101.9 | .9203 | .9989 | 1,001 |
| 11 | 90.74 | 1.161 | 1.260 | 794.0 |
| 12 | 80.81 | 1.463 | 1.588 | 629.6 |
| 13 | 71.96 | 1.845 | 2.003 | 499.3 |
| 14 | 64.08 | 2.327 | 2.525 | 396.0 |
| 15 | 57.07 | 2.934 | 3.184 | 314.0 |
| 16 | 50.82 | 3.700 | 4.016 | 249.0 |
| 17 | 45.26 | 4.666 | 5.064 | 197.5 |
| 18 | 40.30 | 5.883 | 6.385 | 156.6 |
| 19 | 35.89 | 7.418 | 8.051 | 124.2 |
| 20 | 31.96 | 9.355 | 10.15 | 98.5 |
| 21 | 28.45 | 11.80 | 12.80 | 78.11 |
| 22 | 25.35 | 14.87 | 16.14 | 61.95 |
| 23 | 22.57 | 18.76 | 20.36 | 49.13 |
| 24 | 20.10 | 23.65 | 25.67 | 38.96 |
| 25 | 17.90 | 29.82 | 32.37 | 30.90 |
| 26 | 15.94 | 37.61 | 40.81 | 24.50 |
| 27 | 14.20 | 47.42 | 51.47 | 19.43 |
| 28 | 12.64 | 59.80 | 64.90 | 15.41 |
| 29 | 11.26 | 75.40 | 81.83 | 12.22 |
| 30 | 10.03 | 95.08 | 103.2 | 9.691 |
| 31 | 8.928 | 119.9 | 130.1 | 7.685 |
| 32 | 7.950 | 151.2 | 164.1 | 6.095 |
| 33 | 7.08 | 190.6 | 206.9 | 4.833 |
| 34 | 6.305 | 240.4 | 260.9 | 3.833 |
| 35 | 5.615 | 303.1 | 329.0 | 3.040 |
| 36 | 5.000 | 382.2 | 414.8 | 2.411 |
| 37 | 4.453 | 482.0 | 523.1 | 1.912 |
| 38 | 3.965 | 607.8 | 659.6 | 1.516 |
| 39 | 3.531 | 766.4 | 831.8 | 1.202 |
| 40 | 3.145 | 966.5 | 1049 | 0.953 |

TABLE 13. — HYGROMETRY

| Dry Thermometer, ° F. | Difference between Dry and Wet-bulb Thermometers | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1° | 2° | 3° | 4° | 5° | 6° | 7° | 8° | 9° | 10° | 11° | 12° | 13° | 14° | 15° |
| 50 | 93 | 87 | 81 | 74 | 68 | 62 | 56 | 50 | 44 | 39 | 33 | 28 | 22 | 17 | 12 |
| 52 | 94 | 88 | 81 | 75 | 69 | 63 | 58 | 52 | 46 | 41 | 36 | 30 | 25 | 20 | 15 |
| 54 | 94 | 88 | 82 | 76 | 70 | 65 | 59 | 54 | 48 | 43 | 38 | 33 | 28 | 23 | 18 |
| 56 | 94 | 88 | 82 | 77 | 71 | 66 | 61 | 55 | 50 | 45 | 40 | 35 | 31 | 26 | 21 |
| 58 | 94 | 89 | 83 | 77 | 72 | 67 | 62 | 57 | 52 | 47 | 42 | 38 | 33 | 28 | 24 |
| 60 | 94 | 89 | 84 | 78 | 73 | 68 | 63 | 58 | 53 | 49 | 44 | 40 | 35 | 31 | 27 |
| 62 | 94 | 89 | 84 | 79 | 74 | 69 | 64 | 60 | 55 | 50 | 46 | 41 | 37 | 33 | 29 |
| 64 | 95 | 90 | 85 | 79 | 75 | 70 | 66 | 61 | 56 | 52 | 48 | 43 | 39 | 35 | 31 |
| 66 | 95 | 90 | 85 | 80 | 76 | 71 | 66 | 62 | 58 | 53 | 49 | 45 | 41 | 37 | 33 |
| 68 | 95 | 90 | 85 | 81 | 76 | 72 | 67 | 63 | 59 | 55 | 51 | 47 | 43 | 39 | 35 |
| 70 | 95 | 90 | 86 | 81 | 77 | 72 | 68 | 64 | 60 | 56 | 52 | 48 | 44 | 40 | 37 |
| 72 | 95 | 91 | 86 | 82 | 78 | 73 | 69 | 65 | 61 | 57 | 53 | 49 | 46 | 42 | 39 |
| 74 | 95 | 91 | 86 | 82 | 78 | 74 | 70 | 66 | 62 | 58 | 54 | 51 | 47 | 44 | 40 |
| 76 | 96 | 91 | 87 | 83 | 78 | 74 | 70 | 67 | 63 | 59 | 55 | 52 | 48 | 45 | 42 |
| 78 | 96 | 91 | 87 | 83 | 79 | 75 | 71 | 67 | 64 | 60 | 57 | 53 | 50 | 46 | 43 |
| 80 | 96 | 91 | 87 | 83 | 79 | 76 | 72 | 68 | 64 | 61 | 57 | 54 | 51 | 47 | 44 |
| 84 | 96 | 92 | 88 | 84 | 80 | 77 | 73 | 70 | 66 | 63 | 59 | 56 | 53 | 50 | 47 |
| 88 | 96 | 92 | 88 | 85 | 81 | 78 | 74 | 71 | 67 | 64 | 61 | 58 | 55 | 52 | 49 |
| 90 | 96 | 92 | 89 | 85 | 82 | 78 | 75 | 72 | 68 | 64 | 62 | 58 | 56 | 53 | 50 |

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